ANALYSIS OF SHORT-PERIOD SEISMIC SIGNALS AND NOISE RECORDED AT LASA AND TFO

HERMAN J. MECKLENBURG
ROBERT P. MASSÉ
SEISMIC DATA LABORATORY

SEPTEMBER 2, 1971

Prepared for
AIR FORCE TECHNICAL APPLICATIONS CENTER
Washington, D.C.

Under
Project VELA UNIFORM

Sponsored by
ADVANCED RESEARCH PROJECTS AGENCY
Nuclear Monitoring Research Office
ARPA Order No. 1714

TELEDYNE GEOTECH
ALEXANDRIA LABORATORIES

DISCLAIMER NOTICE

THIS DOCUMENT IS THE BEST QUALITY AVAILABLE.

COPY FURNISHED CONTAINED A SIGNIFICANT NUMBER OF PAGES WHICH DO NOT REPRODUCE LEGIBLY.

Neither the Advanced Research Projects Agency nor the Air Force Technical Applications Center will be responsible for information contained herein which has been supplied by other organizations or contractors, and this document is subject to later revision as may be necessary. The views and conclusions presented are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the Advanced Research Projects Agency, the Air Force Technical Applications Center, or the U.S. Government.

UNCLASSIFIED
Security Classification

DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author)
Teledyne Geotech
Alexandria, Virginia

2a. REPORT SECURITY CLASSIFICATION
Unclassified

2b. GROUP

3. REPORT TITLE
ANALYSIS OF SHORT-PERIOD SEISMIC SIGNALS AND NOISE RECORDED AT LASA AND TFO

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)
Scientific

5. AUTHOR(S) (Last name, first name, initial)
Mecklenburg, Herman J. and Massé, Robert P.

6. REPORT DATE
September 21,1971

7a. TOTAL NO. OF PAGES
[illegible]

7b. NO. OF REFS
12

8a. CONTRACT OR GRANT NO.
F33657-72-C-0009

b. PROJECT NO.
VELA T/2706

c. ARPA Order No. 1714

d. ARPA Program Code No. 2F-10

9a. ORIGINATOR'S REPORT NUMBER(S)
276

9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)

10. AVAILABILITY/LIMITATION NOTICES
APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.

11. SUPPLEMENTARY NOTES

12. SPONSORING MILITARY ACTIVITY
ADVANCED RESEARCH PROJECTS AGENCY
NUCLEAR MONITORING RESEARCH OFFICE
WASHINGTON, D.C.

13. ABSTRACT

Short-period beams were formed for twenty-four events recorded at both the LASA and TFO arrays. The mean RMS noise in the frequency range 0.4-3.0 Hz for the LASA beams was 0.16mμ, and for the TFO beams 0.13mμ. Noise reduction by beam formation in the range 0.4-3.0 Hz varied from 17 to 23 db for LASA, from 12 to 18 db for the 37-sensor TFO array, and from 6 to 14db for the 19-sensor TFO subarray. Averaging over several source regions in the distance range $25° < \Delta < 90°$, the signal-to-noise ratio for LASA was about one db better than that of TFO for common events. The improvement in signal-to-noise ratio for LASA beams was found to increase 4 db by changing the number of sensors employed in the beams from 48 to 340 while keeping the minimum sensor spacing $\Delta \geq$ 1km.

14. KEY WORDS

LASA
TFO
Beamforming
Signal-to-noise
Array Efficiency

Security Classification

ANALYSIS OF SHORT-PERIOD SEISMIC SIGNALS AND NOISE RECORDED AT LASA AND TFO

Seismic Data Laboratory Report No. 276

AFTAC Project No.:	VELA T/2706
Project Title:	Seismic Data Laboratory
ARPA Order No.:	1714
ARPA Program Code No.:	2F-10
Name of Contractor:	TELEDYNE GEOTECH
Contract No.:	F33657-72-C-0009
Date of Contract:	01 July 1971
Amount of Contract:	$ 1,290,000
Contract Expiration Date:	30 June 1972
Project Manager:	Royal A. Hartenberger (703) 836-7647

P. O. Box 334, Alexandria, Virginia

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.

ABSTRACT

Short-period beams were formed for twenty-four events recorded at both the LASA and TFO arrays. The mean rms noise in the frequency range 0.4-3.0 Hz for the LASA beams was 0.16 mμ, and for the TFO beams 0.13 mμ. Noise reduction by beam formation in the range 0.4-3.0 Hz varied from 17 to 23 db for LASA, from 12 to 18 db for the 37-sensor TFO array, and from 6 to 14 db for the 19-sensor TFO subarray. Averaging over several source regions in the distance range $25° < \Delta < 90°$, the signal-to-noise ratio for LASA was about 1 db better than that of TFO for common events. The improvement in signal-to-noise ratio for LASA beams was found to increase 4 db by changing the number of sensors employed in the beams from 48 to 340 while keeping the minimum sensor spacing $\Delta \geq 1$ km.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF FIGURES (Cont'd.)

LIST OF TABLES

INTRODUCTION

During the last five years a series of studies have been made to evaluate the performance of the LASA short-period array. In particular, the effectiveness of simple beams in improving the signal-to-noise ratio (S/N) has been determined using the original LASA short-period configuration with 525 sensors (Chiburis and Hartenberger, 1966a, 1966b, 1967). The improvement in signal-to-noise ratio found in these studies for LASA is 15 to 18 db in the frequency range 0.4 to 3.0 Hz, with a noise reduction of 18 to 21 db. The rms noise level was determined to average 0.2 mμ for the beams. Several studies have also been conducted on the beamforming capabilities of the 37 element TFO short-period array (Clark, 1968; Phillips and Kelley, 1968). Values of 11 to 12 db improvement in signal-to-noise ratio and noise reduction values in the range 10 to 13.7 db were obtained in these studies. More recently comparison of film data from the LASA and TFO Kuril Island beams has been made (Clark, 1970), in which it was determined that the detection capability of the two arrays is approximately equal for events in the Kuril Islands region.

The purpose of the present study is to compare the performance of simple beamforming of the LASA and TFO short-

period arrays using a set of world-wide events which were recorded by both arrays. For three of these events, beams using the full LASA short-period array were compared with beams from the full TFO short-period array. For an additional 21 events, approximately 19 TFO short-period elements were employed to construct beams which were compared with the beams from the full LASA short-period array. Short-period beams for five events were also computed using only 18 or 19 sensors of both the LASA and TFO arrays. These beams were then compared and evaluated. Finally, an analysis was made of the LASA short-period beams as a function of the number of sensors used to form the beams.

ANALYSIS OF LASA AND TFO BEAMS

In the analysis of simple beamforming of LASA and TFO short-period array data, the signal amplitude was defined as one-half of the absolute value of the largest peak-to-peak amplitude in the first ten seconds of the signals. The rms noise amplitude was measured in a time sample 40 seconds long, preceding the arrival time of the P phase for the event being processed. Signal-to-noise ratio is defined as the ratio of signal amplitude to rms noise amplitude. The mean of the signal amplitudes, the mean of the S/N values, and the mean of the rms amplitude of the noise were computed using all traces included in each beam. In the tabulations below, these quantities are listed under the column heading "Mean". For the beams, signal amplitudes and S/N values were computed; these are tabulated under the column heading "Sum"; the rms amplitude of the noise was determined and is presented under the column heading "rms". The improvement in signal-to-noise ratio (in db) of the beam over the mean signal-to-noise ratio on the individual traces is defined as:

$$20 \log \left(\frac{\text{S/N ratio for the beam}}{\text{Mean S/N ratio over all traces in beam}} \right).$$

The short-period instruments of the LASA and TFO arrays were used to form beams for twenty-four events. The source parameters of these events are listed in Table I, and the epicenters are shown in Figure 1. The amplitude data for the individual traces and the beams are given in Table II for the case where all traces have been initially band-pass filtered 0.4 to 3.0 Hz. The band-pass filter response is shown in Figure 2. Travel time anomalies (Chiburis, 1968) were used in forming the LASA beams.

The mean rms noise amplitudes for LASA and TFO are shown in Figure 3. The mean rms noise amplitudes for LASA range from 1.0 to 2.4 mμ, while most of the TFO mean rms noise amplitudes fall between 0.3 and 0.7 mμ.

The noise reduction at LASA and TFO by beam formation is shown in Figure 4. Noise reduction of between 17 and 23 db (with a mean of 20.0 db) is attained by the LASA beams. Using approximately 19 sensors, the noise reduction of the TFO beams ranges from 6 to 14 db with a mean of 10.0 db. For the full TFO array, noise reduction values of 11.8 db, 14.7 db and 17.7 db (giving a mean of 14.7 db) were obtained. These values at TFO compare with the noise reduction values for the full array of 10 to 13 db found by Clark (1968) and 13.7 db at 1.0 Hz determined by Phillips and Kelley (1968).

The mean rms noise amplitudes on the LASA and TFO beams are thus 0.16 mμ and 0.13 mμ respectively. A previous study of LASA short-period beams (Chiburis and Hartenberger, 1967) found a mean rms noise amplitude of 0.2 mμ for 41 events using 525 sensors.

Improvement in signal-to-noise ratio for the LASA and TFO beams is given in Figure 5. LASA beams provide 13 to 19 db improvement, while TFO beams give only 4 to 13 db improvement for approximately 19 sensors, and 11 to 15.5 db improvement for the full array. Clark (1968) found the beamforming improvement in signal-to-noise ratio for the full TFO array to be between 11 to 12 db for four events; and Phillips and Kelley (1968) obtained 12 db improvement at frequencies near 1.0 Hz. The improvement in signal-to-noise ratio minus the theoretically expected $n^{1/2}$ improvement is shown in Figure 6. TFO beams can be seen to range from 1 db better to about 8 db worse than the theoretically expected improvement. The LASA beams are from 6 db to 12 db down from $n^{1/2}$ values.

The ratio of the signal-to-noise ratio for the TFO beam to the signal-to-noise ratio for the LASA beam was computed for each of the twenty-four events processed. These ratios are presented in Figures 7 and 8. The Gutenberg "B" factors were used to reduce the variation in signal amplitudes caused

by the difference in epicentral distances of the two arrays from a given earthquake. The distance-corrected ratio of TFO S/N to LASA S/N is shown in Figure 9. The distance correction was not very effective for events in the Hindu Kush-Sinkiang region. TFO lies in the shadow zone of the core for this region, while LASA does not. Averaging over many source regions but excluding the Hindu Kush-Sinkiang region, which is in the shadow zone for TFO, and also excluding all events closer than 25 degrees, i.e., the Mexican events, the signal-to-noise ratio at TFO is found to be 3.9 db lower on the average than at LASA. Correcting for the fact that we did not use the full TFO array of 37 elements on the events, and assuming $n^{1/2}$ improvement in signal-to-noise ratio, yields an average increase of signal-to-noise ratio for the full TFO array of 2.8 db. Thus the net difference is 1.1 db in favor of LASA. Clark's (1970) results are consistent: he found that the LASA Kuril beam was equal to or slightly better than the TFO Kuril beam in detecting events lying within the TFO and LASA beams' 3 db contours.

The signal-to-noise ratio for individual LASA subarray beams was plotted for events in three regions: the Fox Islands (Figure 10), the Kurils and Hokkaido (Figure 11) and Mexico (Figure 12). For each of these regions, the pattern

of the subarray beams' signal-to-noise ratio was similar for the different events within the region. The same result was obtained for three North Columbian earthquakes by Chiburis and Hartenberger (1966). For events located in different regions, the patterns of signal-to-noise ratio can be seen to be different (Figures 10, 11 and 12). This similarity of subarray amplitude patterns for events in the same region and dissimilarity for events in different regions was also noted by Klappenberger (1967a, 1967b).

LASA and TFO beams were formed for five events using a band pass filter of 0.6 to 2.0 Hz (Figure 2) on all traces in the beams. The amplitude data for the individual traces and the beams are given in Table III. The difference in the signal-to-noise ratio of beams with traces prefiltered by the 0.6-2.0 Hz band pass filter and the 0.4-3.0 Hz band pass filter is shown in Figure 13 for LASA and TFO. The 0.6-2.0 Hz band pass filter seems, in general, to work better at both LASA and TFO than does the 0.4-3.0 Hz band pass filter. On the average, LASA improves signal 0.4 db more than does TFO, a difference which is probably less than the statistical uncertainty.

ANALYSIS OF BEAMS FROM A SIMILAR CONFIGURATION OF SHORT-PERIOD SENSORS AT LASA AND TFO

The first 19 short-period sensors of TFO (Z1 through Z19) and 19 sensors of the LASA E3 subarray were used to form beams for five events. The 19 sensors of E3 were chosen so as to approximate as closely as possible the array configuration of the first 19 TFO short-period sensors (Figure 14). The individual traces were band-pass filtered 0.4 to 3.0 Hz prior to beam formation. Amplitude data for the individual traces and the beams are given in Table IV. The mean rms short-period noise amplitudes, the noise reduction, and the improvement in signal-to-noise ratio of the beams for subarray E3 and TFO are shown in Figures 15, 16, and 17 respectively. The ratio of the signal-to-noise ratio for the TFO beam to the signal-to-noise ratio for the LASA E3 beam is shown in Figure 18. This same ratio, corrected for the difference in epicentral distances to LASA and to TFO, is shown in Figure 19. Excluding the Sinkiang event in the shadow zone for TFO, the signal-to-noise ratio at TFO is better than that obtained from the E3 subarray of LASA for three of the four events. This is expected, since LASA has a higher noise level (Figure 15), and the same number of sensors with almost the same spacing was used in the formation of both the LASA and TFO beams.

ANALYSIS OF LASA BEAMS AS A FUNCTION OF THE NUMBER OF SENSORS

To evaluate the signal-to-noise ratio improvement of the LASA array as a function of the number of sensors, four different array configurations were examined. Array configuration I employed all sensors in all subarrays. Configuration II used all sensors in subarrays B through D, making a total of approximately 208 sensors. Configuration III included only the sensors in the center and the outer two subarray rings for subarrays B through D, together with the center sensor of subarray A (a total of approximately 84 sensors). Configuration IV used the sensors in the outer subarray ring, the center sensor of subarrays B through D and the center sensor of subarray A (a total of approximately 48 sensors). The improvement in signal-to-noise ratio of beams for each array configuration is given in Table [illegible], and shown as a function of the number of sensors in Figure 20. The minimum sensor spacing, Δ, for the array configurations I, II, and III is $\Delta \geq 1$ km. For configuration IV, $\Delta \geq 3$ km. The diameter of the array configurations II through IV was the same (~53 km) and for array configuration I the diameter was about 200 km.

From Figure 20, the actual improvement in signal-to-noise ratio can be seen to be less than the theoretical value of $n^{1/2}$ by 7 db for $n=340$ and by 3 db for $n=48$. As has been shown by previous work (Hartenberger, 1967, 1968; Hartenberger and Van Nostrand, 1970), this difference between theoretical and actual improvement in signal-to-noise ratio is due both to noise correlation for small sensor spacing and to signal losses in the beamforming process. The average gain in the improvement of signal-to-noise ratio to be derived from increasing the number of sensors from 48 to 340 is only 4 db. Hartenberger and Van Nostrand (1970) found that, by choosing the sensors so as to make $\Delta \geq 20$ km for $n = 51$, the beams composed of only 51 traces reduce the rms noise amplitude and improve the signal-to-noise ratio to within 1 db of that produced by 525 sensor beams.

This small gain in signal-to-noise ratio derived from using 340 sensors, rather than some much smaller number suggests, of course, that reduction of the number of active sensors at the LASA array should be considered. Defining the efficiency of the array as the noise reduction in db per sensor, and assuming $n^{1/2}$ reduction in noise, then the efficiency E is given by:

$$E = \frac{20 \log_{10} n^{1/2}}{n}$$

The efficiency is shown in Figure 21 for values of n from 1 to 1000. A 200-sensor array can be seen to be almost as efficient as a 340 sensor array. The maximum in the curve shown in Figure 21 occurs at a value of n = e (approximately 2.718), which can be derived by evaluating $\partial E/\partial n = 0$. An additional factor in any consideration of LASA sensor reduction is the signal-to-noise ratio of the individual subarray beams to the epicenter regions of greatest interest. If possible, subarrays with high signal-to-noise ratio on beams pointed to such regions should be retained in the reduced array.

CONCLUSIONS

From the analysis of short-period LASA and TFO beams for twenty-four events recorded at both arrays, we conclude:

(1) For LASA, in the frequency range 0.4-3.0 Hz the mean rms noise amplitude ranges from 1.0 to 2.4 mμ; the noise reduction by beam formation is from 17 to 23 db, the improvement in signal-to-noise ratio is 13 to 19 db, and the mean rms noise amplitude of the beams is 0.16 mμ.

(2) For TFO, in the range 0.4-3.0 Hz the mean rms noise amplitude ranges from 0.3 to 0.7 mμ. The noise reduction by beaming 19 sensors is 6 to 14 db, with an improvement in signal-to-noise ratio of 4 to 13 db. For the full TFO array, the noise reduction of the beam is 11.8 to 17.7 db, and the improvement in signal-to-noise ratio is 11 to 15.5 db. The mean rms noise amplitude of all the TFO beams is 0.13 mμ.

(3) The signal-to-noise ratio in the range 0.4-3.0 Hz for the full LASA beam is estimated to be 1.1 db better than the full TFO beam; this is an average over 17 events in the distance range 25° to 90°.

(4) The pattern of signal-to-noise ratio for individual LASA subarray beams is consistent for any given source region, but varies from region to region.

(5) The signal-to-noise ratio for a 19-sensor beam from

the LASA E3 subarray is, in general, less than the 19-sensor TFO beam, due to the larger noise amplitude at the E3 subarray.

(e) The improvement in signal-to-noise ratio is increased 4 db by changing from 48 to 340 sensors and keeping the minimum between-sensor spacing $\Delta \geq 1$ km.

Acknowledgements

We wish to thank Royal A. Hartenberger and Robert Blandford for their very helpful discussions.

REFERENCES

Chiburis, E.F. and Hartenberger, R.A., 1966a, LASA signal and noise amplitudes for three teleseismic events: Seismic Data Laboratory Report No. 151, Teledyne Geotech, Alexandria, Virginia.

Chiburis, E.F. and Hartenberger, R.A., 1966b, Signal-to-noise ratio improvement by time-shifting and summing LASA seismograms: Seismic Data Laboratory Report No. 164, Teledyne Geotech, Alexandria, Virginia.

Chiburis, E.F. and Hartenberger, R.A., 1967, Signal-to-noise ratio improvement by beamforming LASA seismograms: Seismic Data Laboratory Report No. 173, Teledyne Geotech, Alexandria, Virginia.

Chiburis, E.F., 1968, LASA travel-time anomalies for 65 regions computed with the Herrin travel-time table, November 1966 version: Seismic Data Laboratory Report No. 204, Teledyne Geotech, Alexandria, Virginia.

Clark, D.M., 1968, Preliminary beamforming study of the TFO-37 array: Seismic Data Laboratory Report No. 216, Teledyne Geotech, Alexandria, Virginia.

Clark, D.M., 1970, LASA and TFO Film Analysis: Technical Memorandum, 27 January, Teledyne Geotech, Alexandria, Virginia.

Hartenberger, R.A., 1967, The effect of the number and spacing of elements on the efficiency of LASA beams: Seismic Data Laboratory Report No. 203, Teledyne Geotech, Alexandria, Virginia.

Hartenberger, R.A., 1968, Supplement to The effect of the number and spacing of elements on the efficiency of LASA beams: Teledyne Geotech, Alexandria, Virginia.

Hartenberger, R.A. and Van Nostrand, R.G., 1970, Influence of number and spacing of sensors on the effectiveness of seismic arrays: Seismic Data Laboratory Report No. 252, Teledyne Geotech, Alexandria, Virginia.

Klappenberger, F.A., 1967a, Distribution of short period P-phase amplitudes over LASA: Seismic Data Laboratory Report No. 187, Teledyne Geotech, Alexandria, Virginia.

Klappenberger, F.A., 1967b, Spatial correlation of amplitude anomalies: Seismic Data Laboratory Report No. 195, Teledyne Geotech, Alexandria, Virginia.

REFERENCES (Cont'd.)

Phillips, D.R. and Kelley, D.S., 1968, Preliminary evaluation of beam-steering capabilities of the TFSO 37-element array: Teledyne Geotech, Technical Report No. 68-47, Garland, Texas.

TABLE I

Source parameters of events analyzed by beam formation.

Event No.	Event	Date	Origin Time	Location Latitude	Location Longitude	Magnitude m_b
1	N. Atlantic	9/06/69	14 30 39.5	36.9N	11.9W	5.7
2	N. Atlantic	10/15/69	12 44 10.0	15.6N	44.9W	5.0
3	Mid. Atlantic	11/06/69	13 21 21.0	3.9N	32.4W	5.0
4	Baja California	8/21/69	14 25 51.5	23.2N	110.6W	5.2
5	Chile/Bolivia	12/11/69	16 56 25.2	21.2S	68.5W	4.5
6	Costa Rica	7/04/69	11 16 01.0	7.4N	82.7W	5.0
7	Fox Island	9/03/69	06 13 05.3	53.1N	169.9W	5.0
8	Fox Island	10/24/69	00 46 14.6	52.2N	168.6W	5.1
9	Gulf of Calif.	8/18/69	07 51 06.9	24.8N	109.1W	5.0
10	Hindu Kush	8/06/69	06 30 57.1	36.4N	70.9E	5.6
11	Hokkaido	8/13/69	07 24 05.1	43.1N	147.0E	4.7
12	Jalisco	8/21/69	13 10 47.4	17.3N	105.4W	4.8
13	Kodiak	7/28/69	06 29 53.9	57.5N	153.9W	5.1
14	Kurils	8/22/69	04 40 26.1	43.1N	148.3E	4.7
15	Kurils	9/06/69	07 43 29.8	43.7N	147.3E	5.5
16	Cst. Mexico	9/07/69	09 36 21.0	16.5N	98.7W	4.8
17	Mexico	10/20/69	13 20 36.5	17.3N	95.2W	5.2
18	Peru	7/04/69	06 32 43.4	4.1S	80.9W	4.0
19	Peru	8/30/69	[illegible] 06 53.5	14.2S	73.3W	4.6
20	Ryukyu	6/19/69	07 03 04.9	28.1N	130.0E	5.5
21	Sinkiang	9/14/69	16 15 24.8	39.7N	74.9E	5.5
22	Tonga Island	7/22/69	13 48 36.5	18.1S	172.5W	5.2
23	Unimak	6/20/69	02 37 51.5	55.2N	162.4W	5.6
24	Yugoslavia	10/27/69	08 10 58.3	44.9N	17.2E	5.3

TABLE 11

Amplitude data for short period array beams - traces band pass filtered (0.4-3.0 Hz).

TFO

Event No.	Event	Date	n	SIGNAL Mean mμ	SIGNAL Sum mμ	SIGNAL Sum/Mean db	NOISE Mean mμ	NOISE rms mμ	NOISE rms/Mean db	S/N Mean	S/N Sum	S/N Sum/Mean db	$n^{1/2}$ db
1	N. Atlantic	9/06/69	10	15.8	15.1	-0.37	0.37	0.10	11.8	43.4	153.6	11.0	12.3
2	S. Atlantic	10/13/69	10	6.8	[illegible]	-0.73	0.30	0.15	-9.1	23.0	57.9	8.0	12.3
3	Mid. Atlantic	11/24/69	11	10.5	15.0	-1.56	0.03	0.12	-18.7	29.7	133.7	13.3	13.4
4	Baja Calif.	8/21/69	10	70.0	63.4	-0.88	0.81	0.10	12.0	178.1	617.2	11.0	12.5
5	Chile/Bolivia	12/11/69	11	6.3	5.1	-1.02	0.08	0.09	[illegible]	10.7	81.0	15.2	13.2
6	Costa Rica	7/08/69	19	22.2	20.1	-0.90	0.37	0.03	9.2	60.9	157.3	8.2	12.9
7	Fox Island	8/03/69	19	19.6	19.1	-0.37	0.81	0.12	10.9	50.3	162.4	10.2	12.9
8	Fox Island	10/28/69	12	13.4	12.0	-0.80	0.06	0.12	11.0	29.9	109.8	11.1	13.1
9	Gulf of Calif.	9/10/69	16	81.1	77.5	-0.99	0.72	0.15	-13.9	97.3	256.6	13.0	12.0
10	Hindu Kush	8/09/69	14	3.3	3.0	-0.97	0.83	0.11	-11.7	[illegible]	26.8	10.7	12.3
11	Hokkaido	8/13/69	17	11.0	11.0	-0.65	0.09	0.25	6.6	25.0	87.8	6.3	12.3
12	Jalisco	8/21/69	19	55.6	51.1	-0.70	0.37	0.10	-11.3	151.6	513.6	10.6	12.9
13	Kodiak	7/29/69	17	60.9	59.2	-0.25	0.33	0.07	-13.0	109.2	797.0	12.5	12.3
14	Kurile	8/22/69	18	7.3	6.9	-0.86	0.30	0.12	9.0	20.6	59.3	9.2	12.5
15	Kurile	9/06/69	18	35.0	35.2	0.18	0.30	0.13	9.3	90.1	278.9	9.2	12.5
16	Cnt. Mexico	9/07/69	19	83.0	71.0	1.35	0.22	0.18	-11.8	175.0	310.0	9.3	12.4
17	Mexico	10/20/69	17	82.0	36.7	1.15	0.08	0.11	-11.9	90.2	353.2	10.0	12.5
18	Peru	7/08/69	18	5.6	4.5	1.05	0.30	0.12	-6.0	35.6	27.2	0.0	13.3
19	Peru	8/30/69	17	9.5	9.9	0.84	0.80	0.15	9.2	20.2	65.6	0.4	12.3
20	Ryukyu	8/19/69	17	3.8	2.3	2.07	0.05	0.18	9.2	8.9	88.8	6.2	12.3
21	Sinkiang	9/18/69	17	2.0	1.5	2.19	0.80	0.16	9.0	8.0	9.7	2.0	12.3
22	Tonga Island	7/22/69	19	16.7	16.1	0.35	0.30	0.13	2.8	56.0	105.0	5.0	12.0
23	Unimak	9/20/69	19	59.3	57.2	-2.35	0.22	0.12	13.0	115.7	325.5	9.0	12.6
24	Yugoslavia	10/27/69	22	13.0	12.3	1.01	0.82	0.12	-10.2	33.4	100.2	9.5	13.4

LASA

Event No.	Event	n	SIGNAL Mean mμ	SIGNAL Sum mμ	SIGNAL Sum/Mean db	NOISE Mean mμ	NOISE rms mμ	NOISE rms/Mean db	S/N Mean	S/N Sum	S/N Sum/Mean db	$n^{1/2}$ db
1	N. Atlantic	333	38.7	21.6	-8.1	2.1	0.15	-22.9	19.0	183.8	17.6	25.25
2	S. Atlantic	329	16.5	11.2	-1.6	1.4	0.15	-19.6	12.2	92.0	17.6	25.10
3	Mid. Atlantic	327	30.9	89.7	-1.9	1.9	0.20	-19.0	20.7	200.1	17.2	25.10
4	Baja Calif.	337	88.5	51.0	-8.3	2.1	0.10	-21.4	89.2	295.1	13.6	25.27
5	Chile/Bolivia	329	31.1	[illegible]	1.2	1.7	0.10	-20.9	19.0	173.8	10.9	25.17
6	Costa Rica	319	111.8	83.2	-8.9	1.4	0.15	-19.8	90.7	830.4	13.7	25.04
7	Fox Island	327	16.5	10.9	-3.7	1.2	0.18	-10.5	16.5	79.1	13.6	25.27
8	Fox Island	337	37.6	20.1	-3.5	2.2	0.20	-20.0	19.0	132.0	16.6	25.27
9	Gulf of Calif.	334	88.2	[illegible]	-5.5	1.0	0.17	-19.3	30.8	139.5	13.3	25.30
10	Hindu Kush	310	109.3	1209.9	-8.7	1.0	0.10	-19.9	133.9	1202.8	17.9	25.31
11	Hokkaido	310	13.1	11.3	-1.2	1.5	0.10	-16.0	10.9	78.2	10.7	24.99
12	Jalisco	301	17.0	82.7	-2.9	1.2	0.10	-20.8	11.6	79.1	16.7	24.78
13	Kodiak	321	89.0	37.8	-2.3	1.0	0.10	-19.9	32.5	106.8	17.8	25.09
14	Kurile	325	[illegible]	9.0	-1.1	1.2	0.10	-20.1	7.0	60.5	15.6	25.13
15	Kurile	300	87.0	89.3	-8.7	1.2	0.11	-21.0	43.7	375.0	10.7	24.29
16	Cnt. Mexico	322	88.6	27.5	-8.5	1.0	0.12	-18.8	45.0	223.7	13.9	25.00
17	Mexico	337	88.5	24.1	-5.0	2.4	0.21	-21.1	20.0	117.8	15.0	25.27
18	Peru	318	11.0	7.6	-1.2	1.3	0.18	-10.6	10.1	55.0	14.7	24.91
19	Peru	333	23.7	20.6	-1.9	2.0	0.10	-21.1	18.8	117.5	19.3	25.22
20	Ryukyu	337	22.8	19.8	-1.2	1.5	0.22	-17.6	18.0	67.9	13.5	25.01
21	Sinkiang	316	7.0	34.7	-3.8	1.9	0.18	[illegible]	81.3	300.5	10.6	25.20
22	Tonga Island	200	14.3	9.5	-1.0	1.0	0.19	-19.5	6.2	83.9	16.8	24.50
23	Unimak	320	22.2	108.8	-3.7	1.0	0.19	-20.2	150.0	1188.3	17.2	25.05
24	Yugoslavia	339	7.6	50.3	-2.6	1.4	0.10	-17.9	50.7	305.8	18.0	25.30

TABLE IV

Amplitude data for short period array beams for LASA E3 and TFO - traces band pass filtered (0.4-3.0 Hz).

Event No.	Event	Array	n	SIGNAL Mean mμ	SIGNAL Sum mμ	SIGNAL Sum/Mean dB	NOISE Mean mμ	NOISE rms mμ	NOISE rms/Mean dB	S/N Mean	S/N Sum	S/N Sum/Mean dB	S/N $n^{1/2}$ dB
3	Mid. Atlantic	TFO	19	10.7	14.7	-1.00	.39	.151	-11.9	20.2	97.3	10.0	12.9
		LASA-E3	19	39.4	31.2	-2.30	2.05	.477	-12.0	18.0	88.3	9.6	12.9
11	Hokkaido	TFO	18	11.2	10.4	-.60	.49	.229	-6.6	22.3	45.5	6.1	12.6
		LASA-E3	18	10.0	10.6	-.67	1.10	.300	-9.1	10.0	30.0	9.3	12.6
18	Peru	TFO	18	5.5	4.3	-1.05	.30	.105	-9.0	18.4	[illegible]	8.9	12.6
		LASA-E3	19	16.2	13.1	-2.04	1.23	.324	-11.5	14.1	39.5	9.9	12.9
21	Sinkiang	TFO	19	2.6	1.3	-2.90	.34	.100	-10.2	7.9	9.0	9.9	12.9
		LASA-E3	18	29.2	23.5	-1.90	1.35	.405	-10.4	22.0	30.0	9.6	12.6
23	Unimak	TFO	19	49.1	37.3	-2.40	.52	.115	-13.0	115.0	325.0	9.0	12.9
		LASA-E3	19	177.0	97.8	-5.40	1.19	.300	-11.9	151.0	525.5	9.5	12.9

TABLE V

Amplitude data for LASA short period array beams using different sensor configurations - traces band pass filtered (0.4-3.0 Hz)

Event No.	Event	Configuration I n	Configuration I S/N($\frac{Sum}{Mean}$) db	Configuration II n	Configuration II S/N($\frac{Sum}{Mean}$) db	Configuration III n	Configuration III S/N($\frac{Sum}{Mean}$) db	Configuration IV n	Configuration IV S/N($\frac{Sum}{Mean}$) db
3	Mid. Atlantic	320	17.56	203	14.45	83	12.13	49	10.18
5	Chile/Bolivia	329	18.92	193	19.79	79	17.41	49	15.30
10	Hindu Kush	340	17.85	204	14.58	83	13.97	49	13.44
15	Kurils	330	16.05	203	16.89	83	15.59	47	14.18
18	Peru	332	18.20	197	16.00	79	14.39	48	12.38

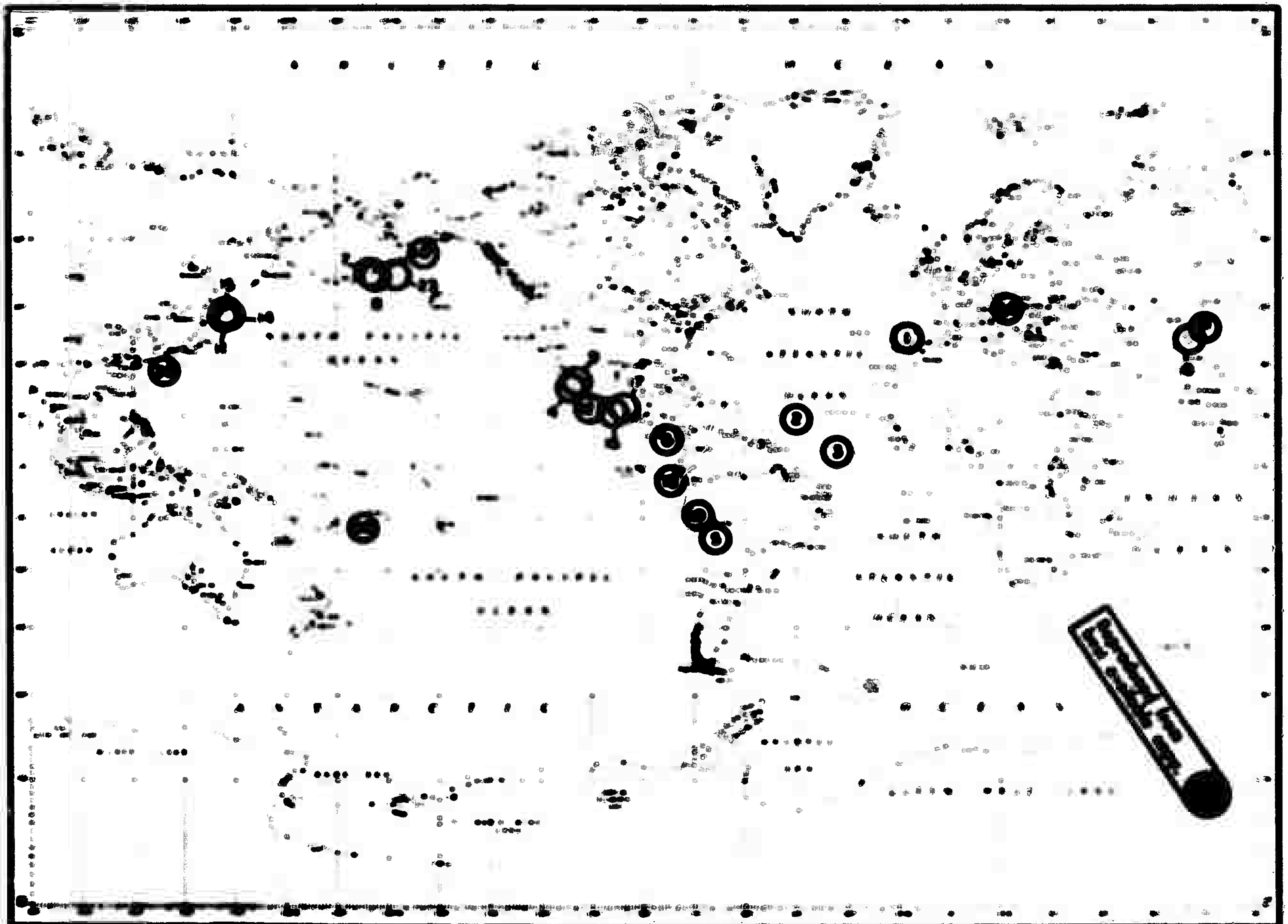

Figure [illegible]. Epicenters of events analyzed by beam formation.

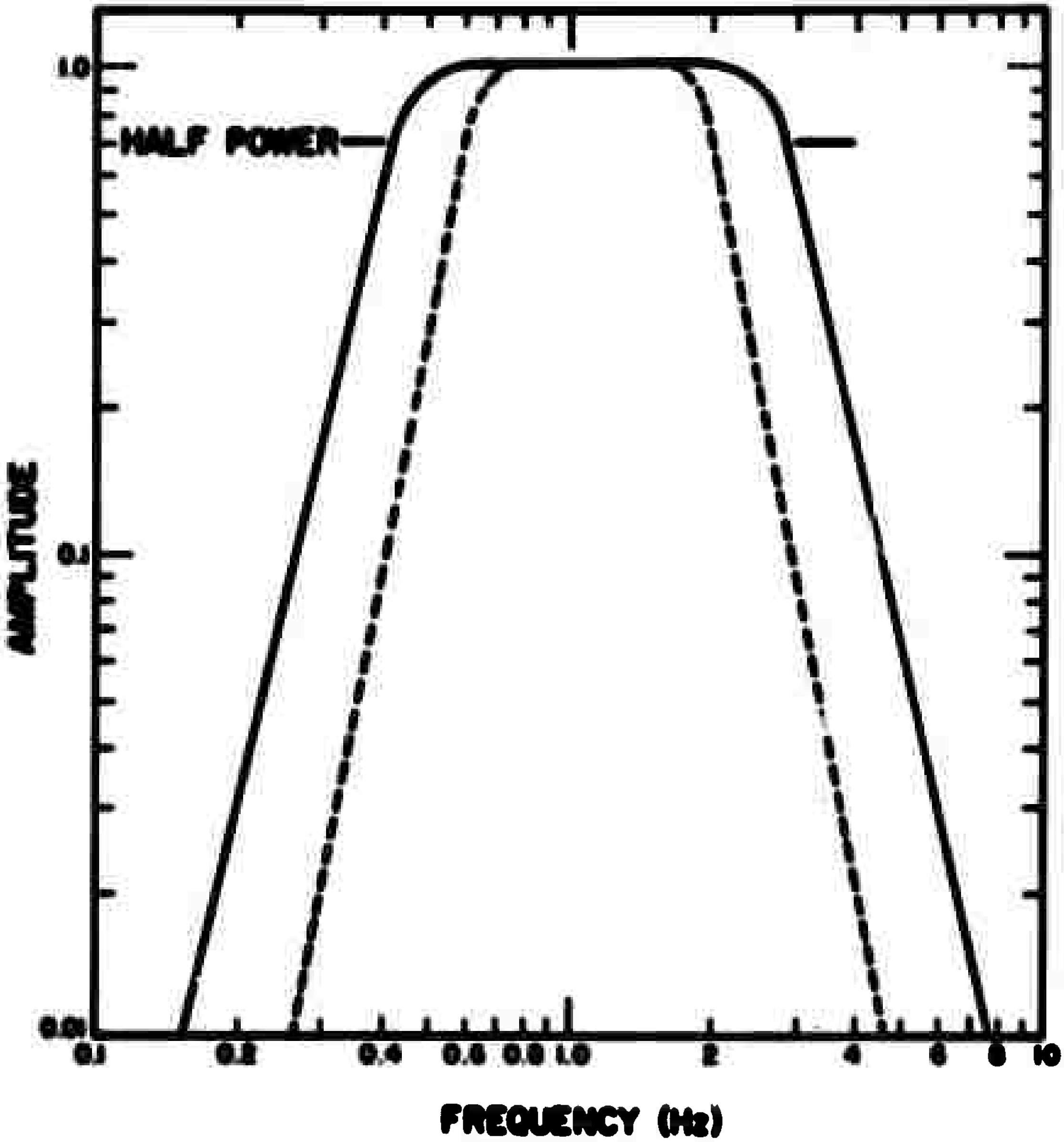

Figure 2. Band pass filters used in data preparation.

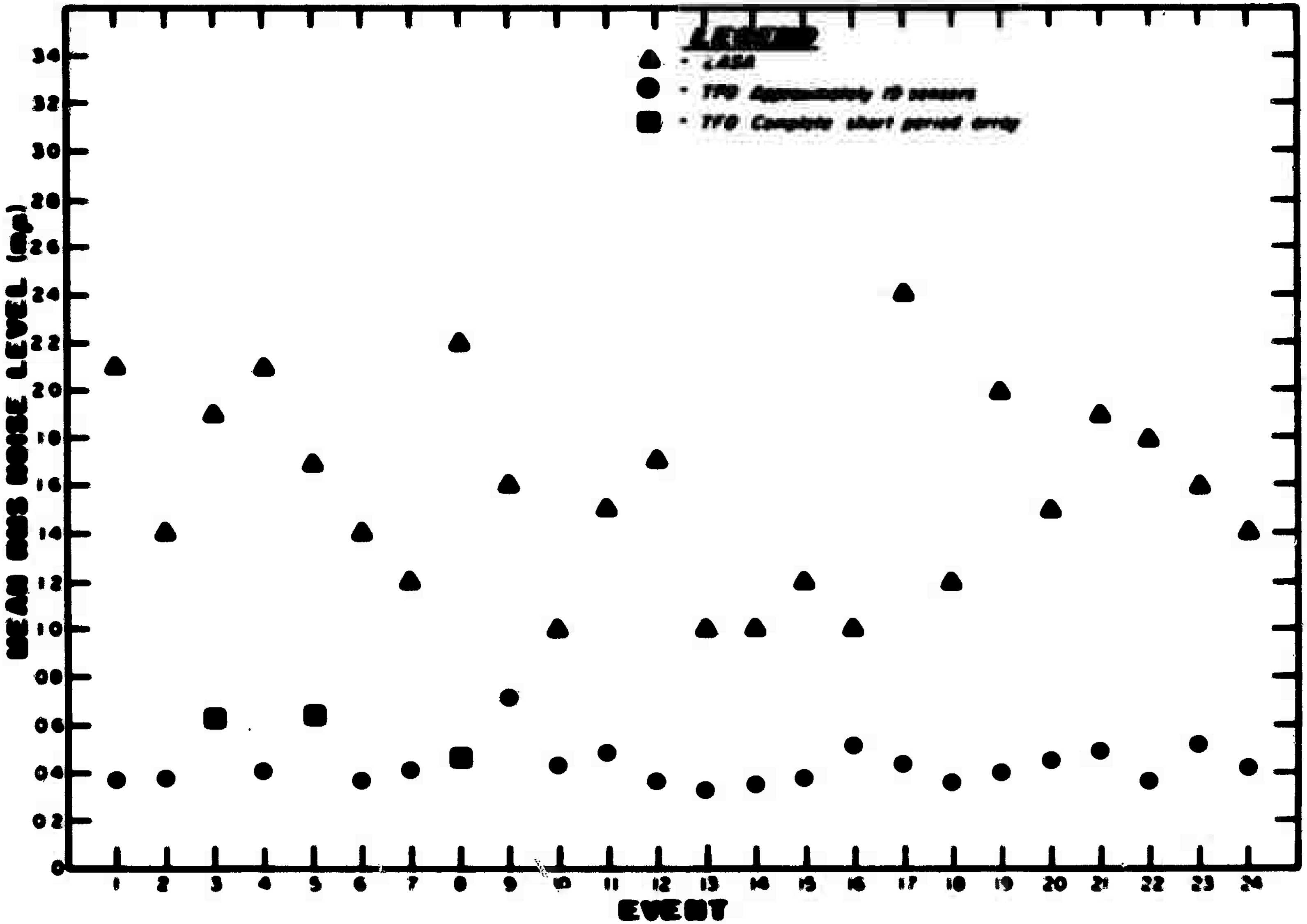

Figure 3. Mean short period rms noise levels at LASA and TFO (Band pass filtered (0.4-3.0 Hz).

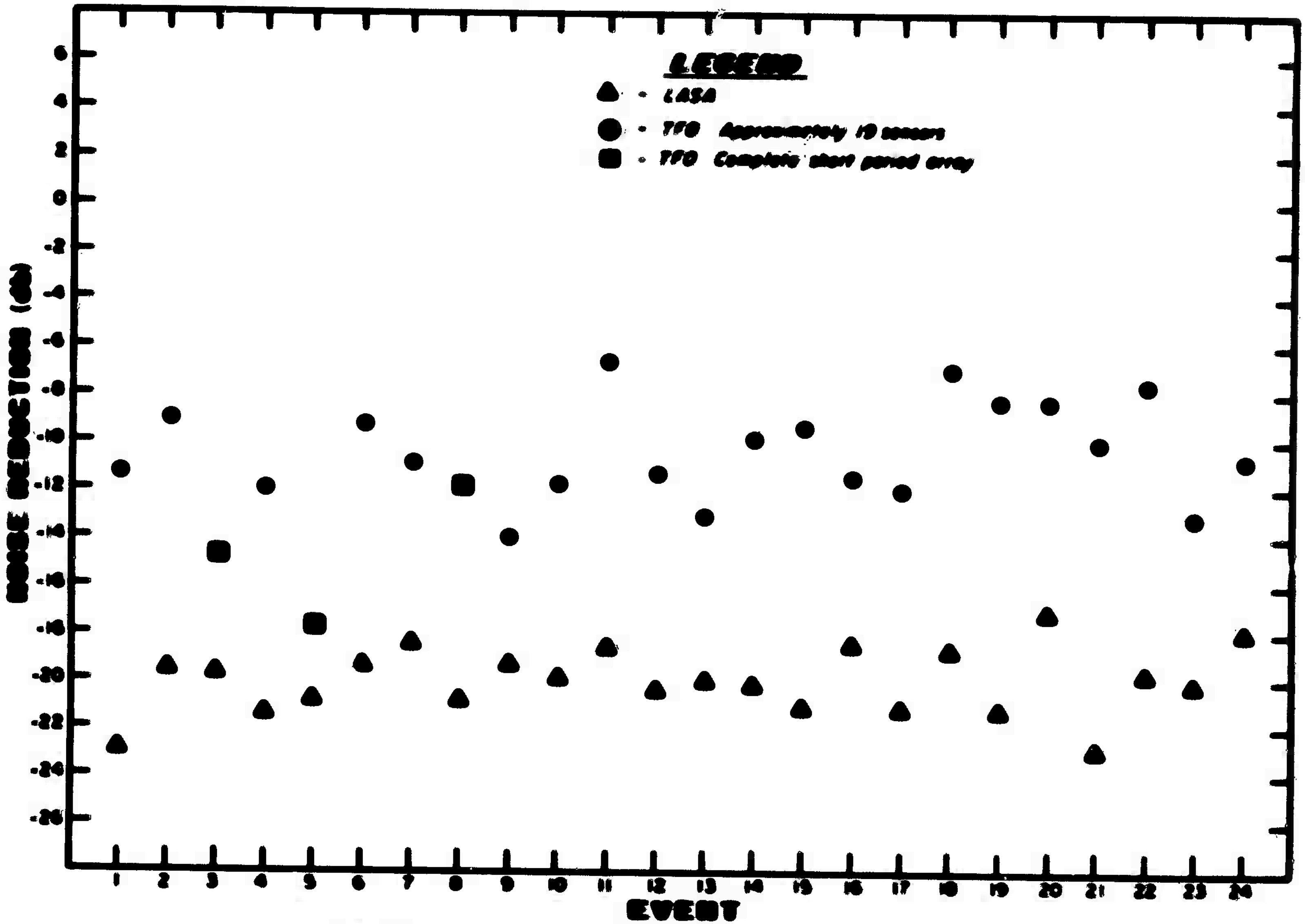

Figure 4. Noise reduction of short period beams of LASA and TFO (Band pass filtered 0.8-3.0 Hz).

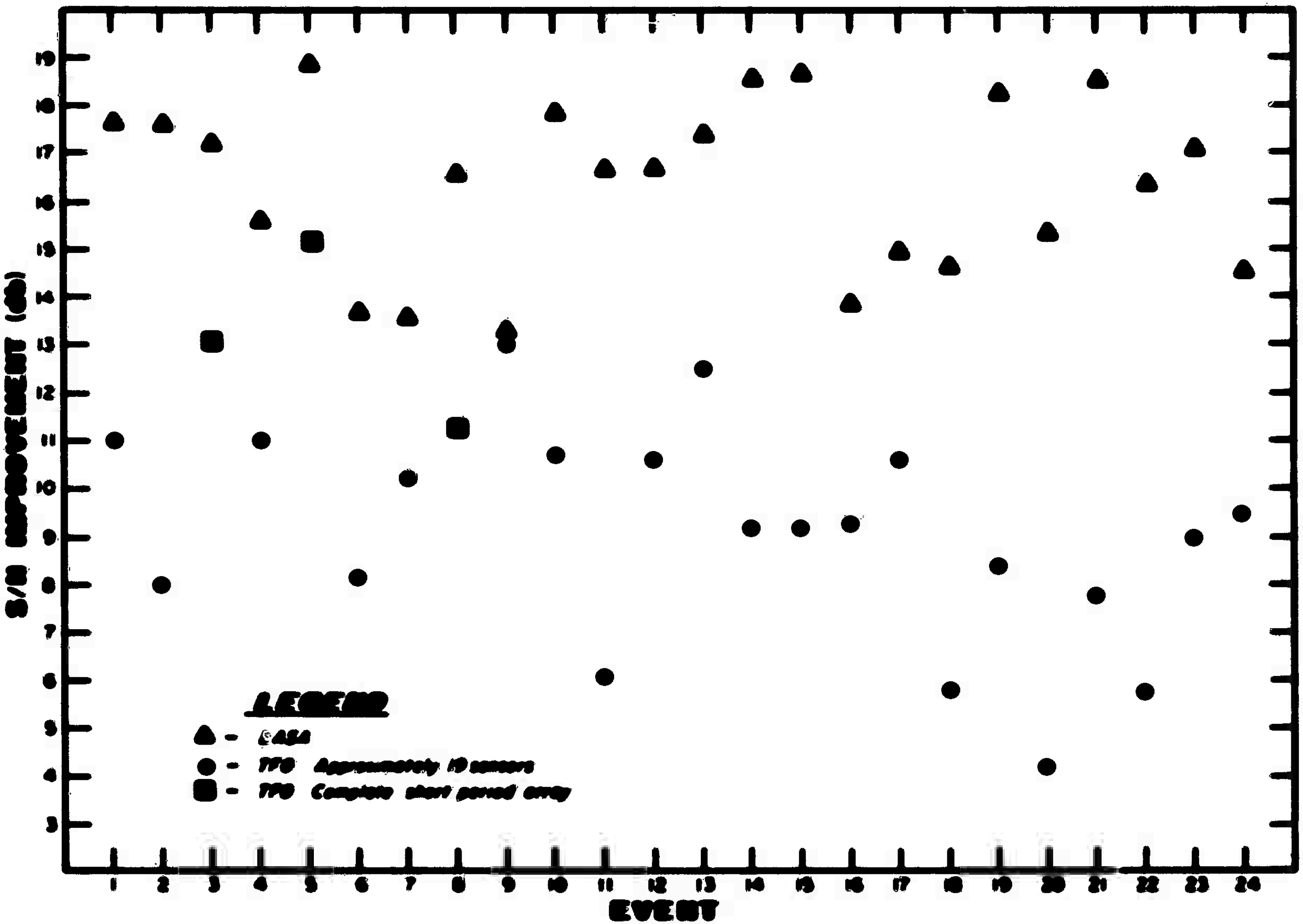

Figure 5. S/N improvement of short period beams of LASA and TFO (Band pass filtered 0.4-3.0 Hz).

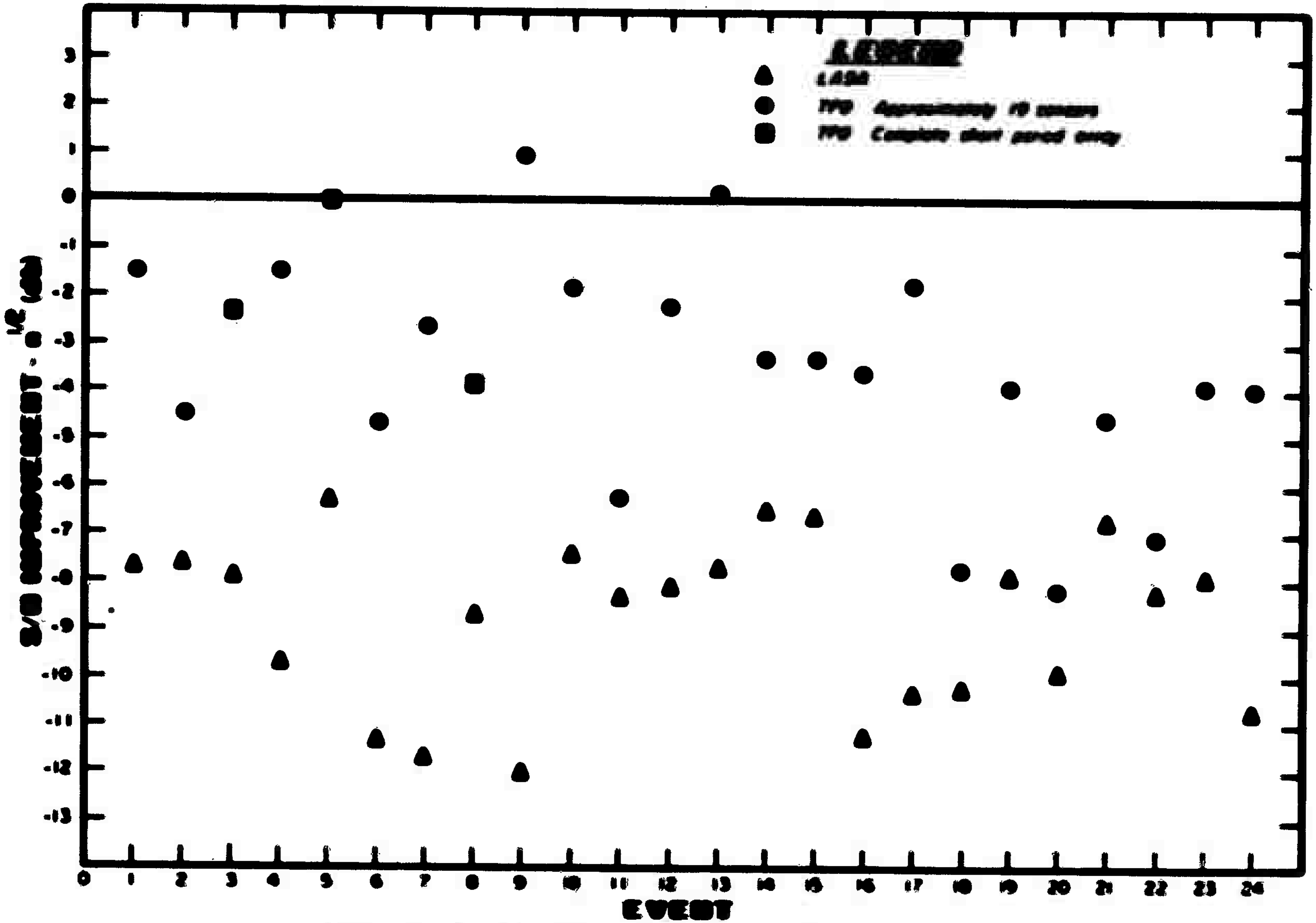

Figure 6. S/N improvement of short period beams of LASA and TFO minus $n^{1/2}$ (band pass filtered 0.4-3.0 Hz).

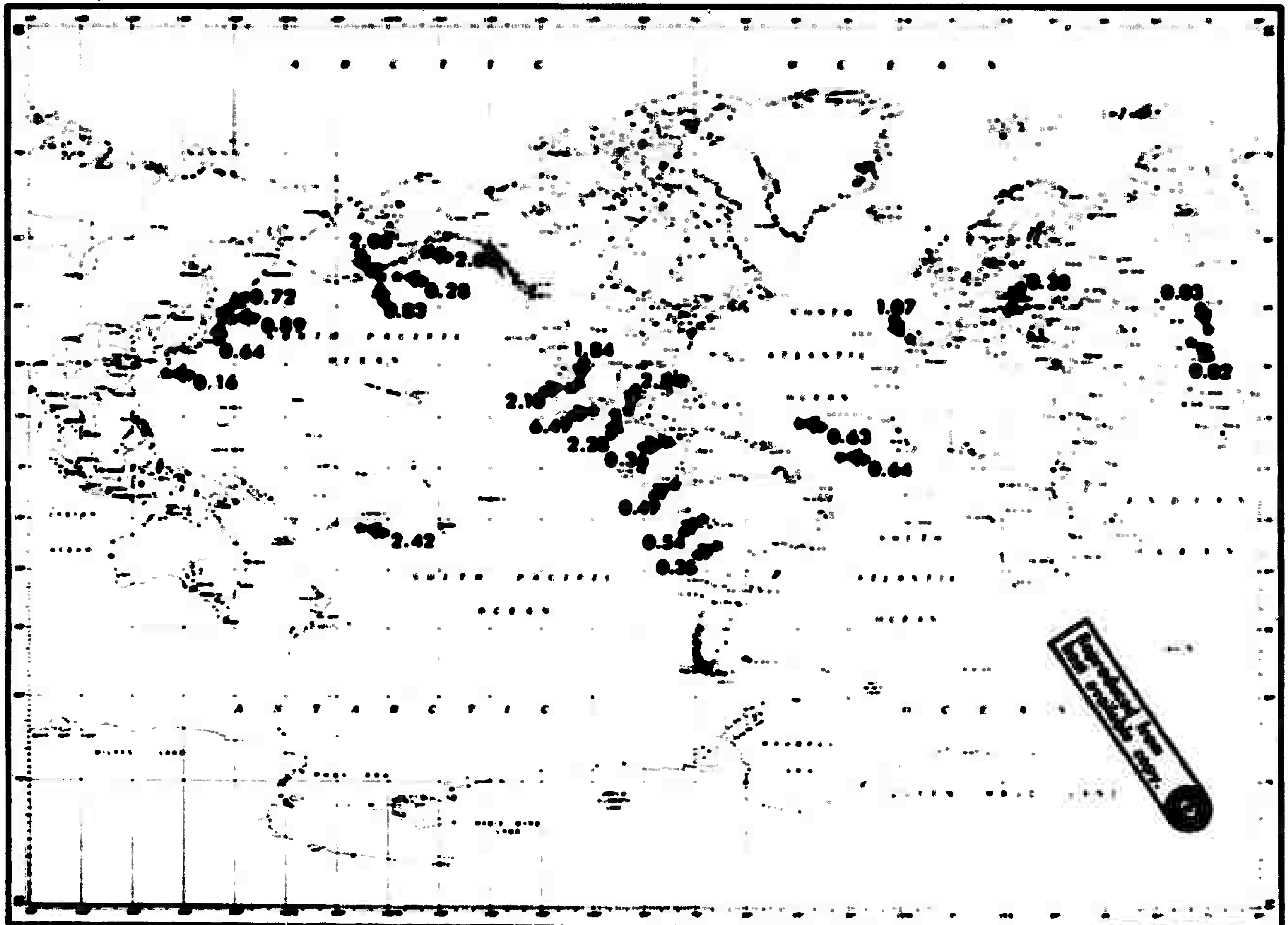

Figure 7. Ratio of the S/N for the TFO beam to the S/N for the LASA beam (Band pass filtered 0.4-3.0 Hz).

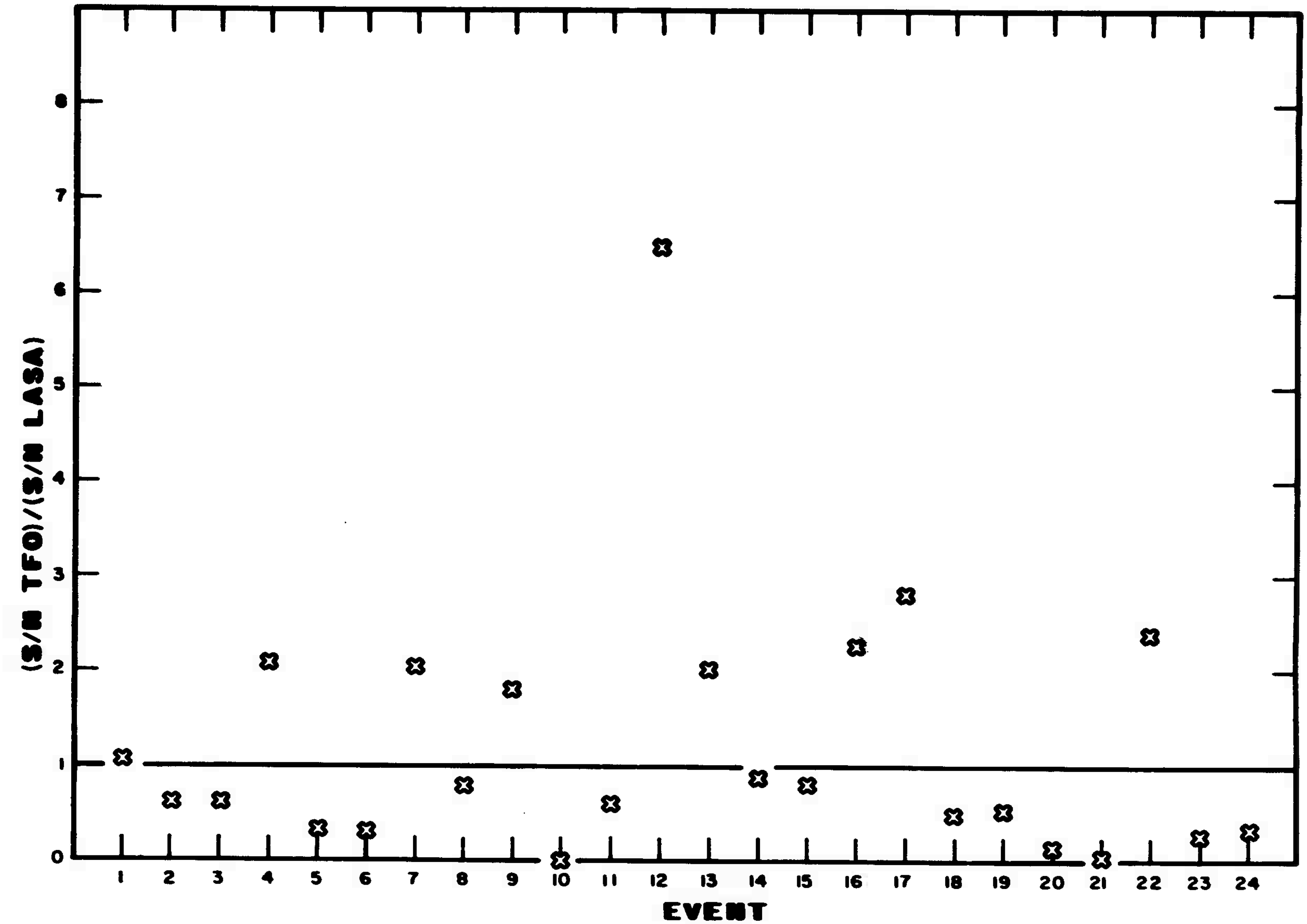

Figure 8. Ratio of the S/N for the TFO beam to the S/N for the LASA beam (Band pass filtered 0.4-3.0 Hz).

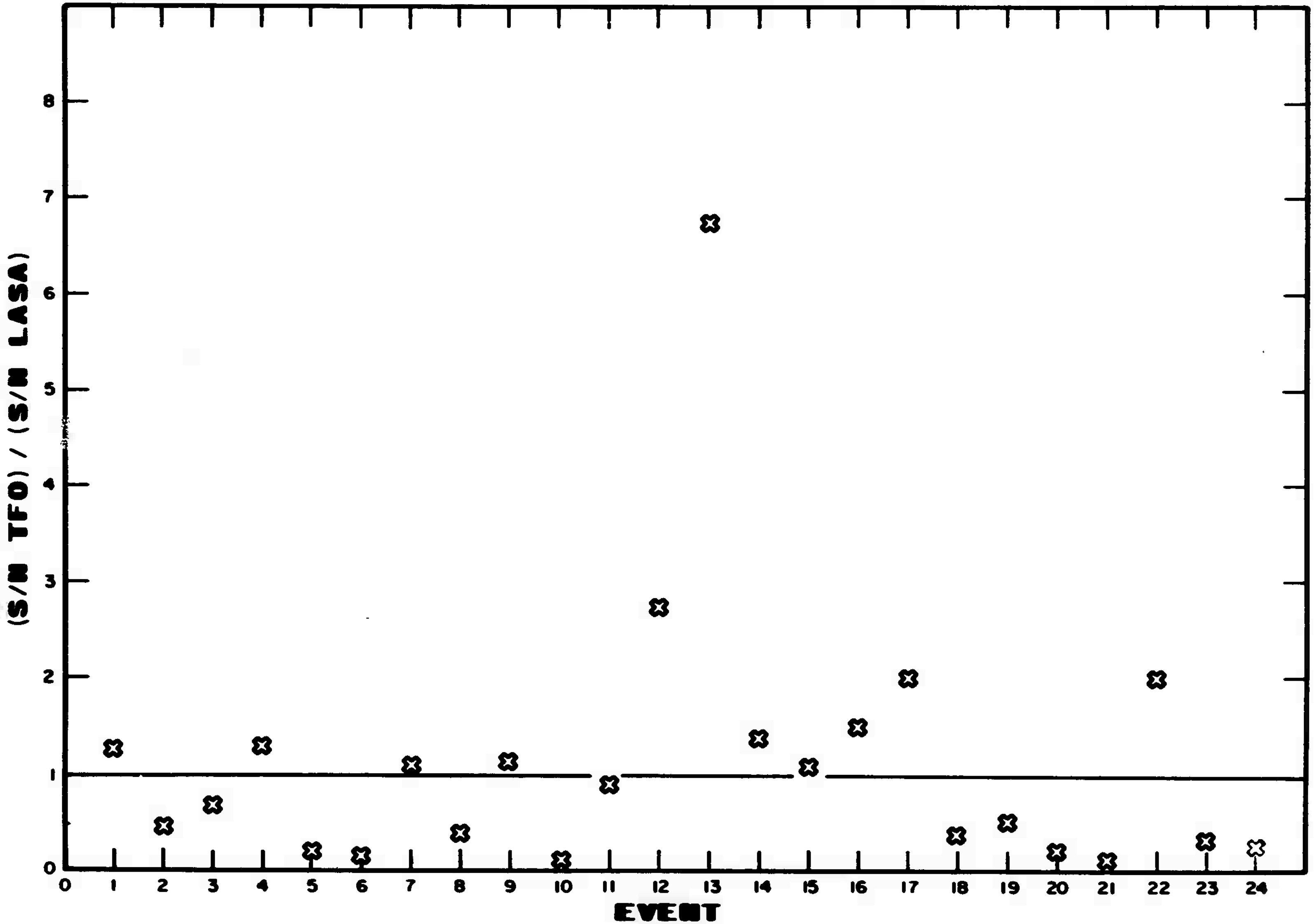

Figure 9. Ratio of the S/N for the TFO beam to the S/N for the LASA beam corrected for the difference in epicentral distances to LASA and to TFO (Band pass filtered 0.4-3.0 Hz).

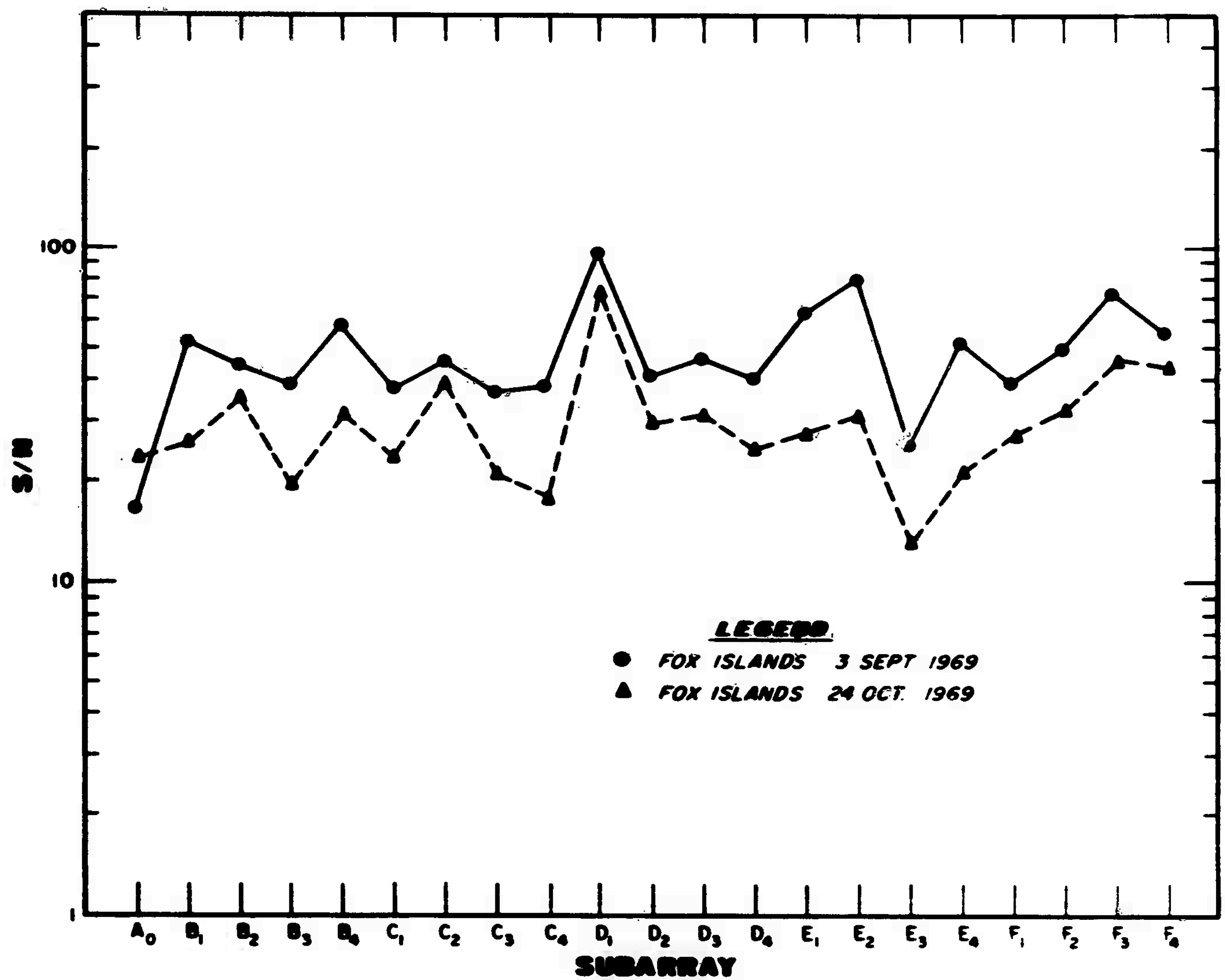

Figure 10. S/N of LASA subarray beams for events in the Fox Islands region (Band pass filtered 0.4-3.0 Hz).

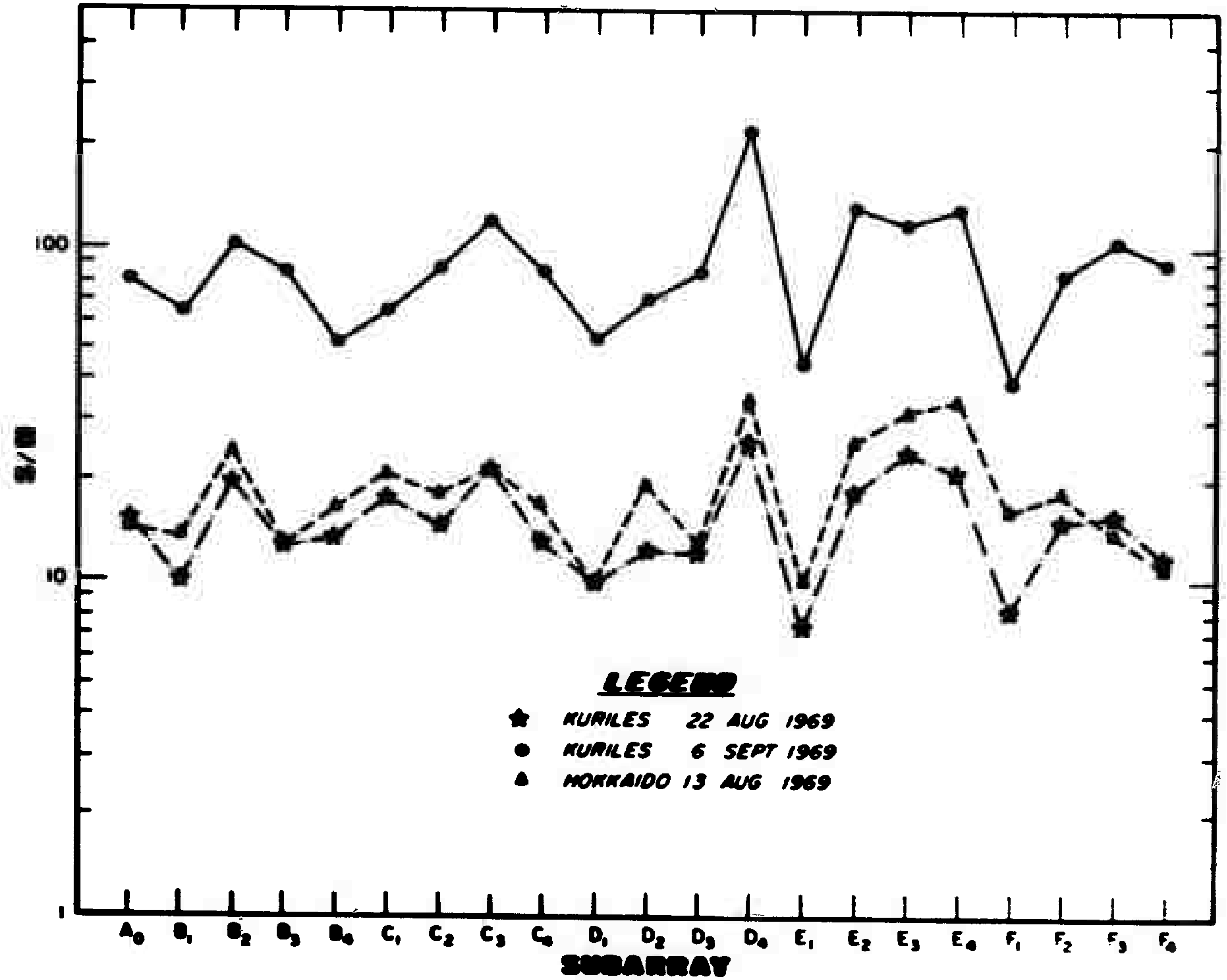

Figure 11. S/N of LASA subarray beams for events in the Kuril Islands and Hokkaido region (Band pass filtered 0.4-3.0 Hz).

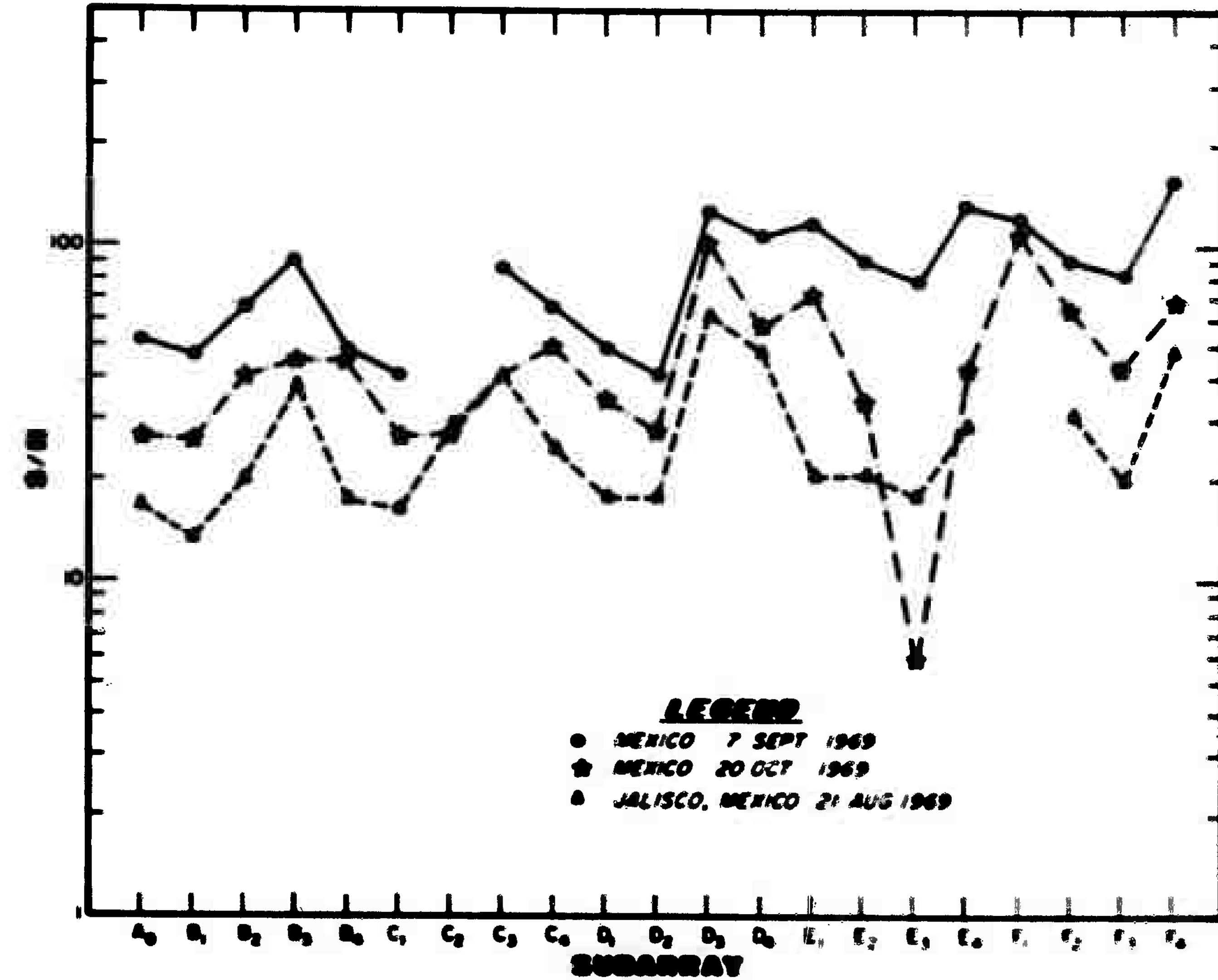

Figure 12. S/N of LASA subarray beams for events in the Mexico region (band pass filtered 0.4-3.0 hz).

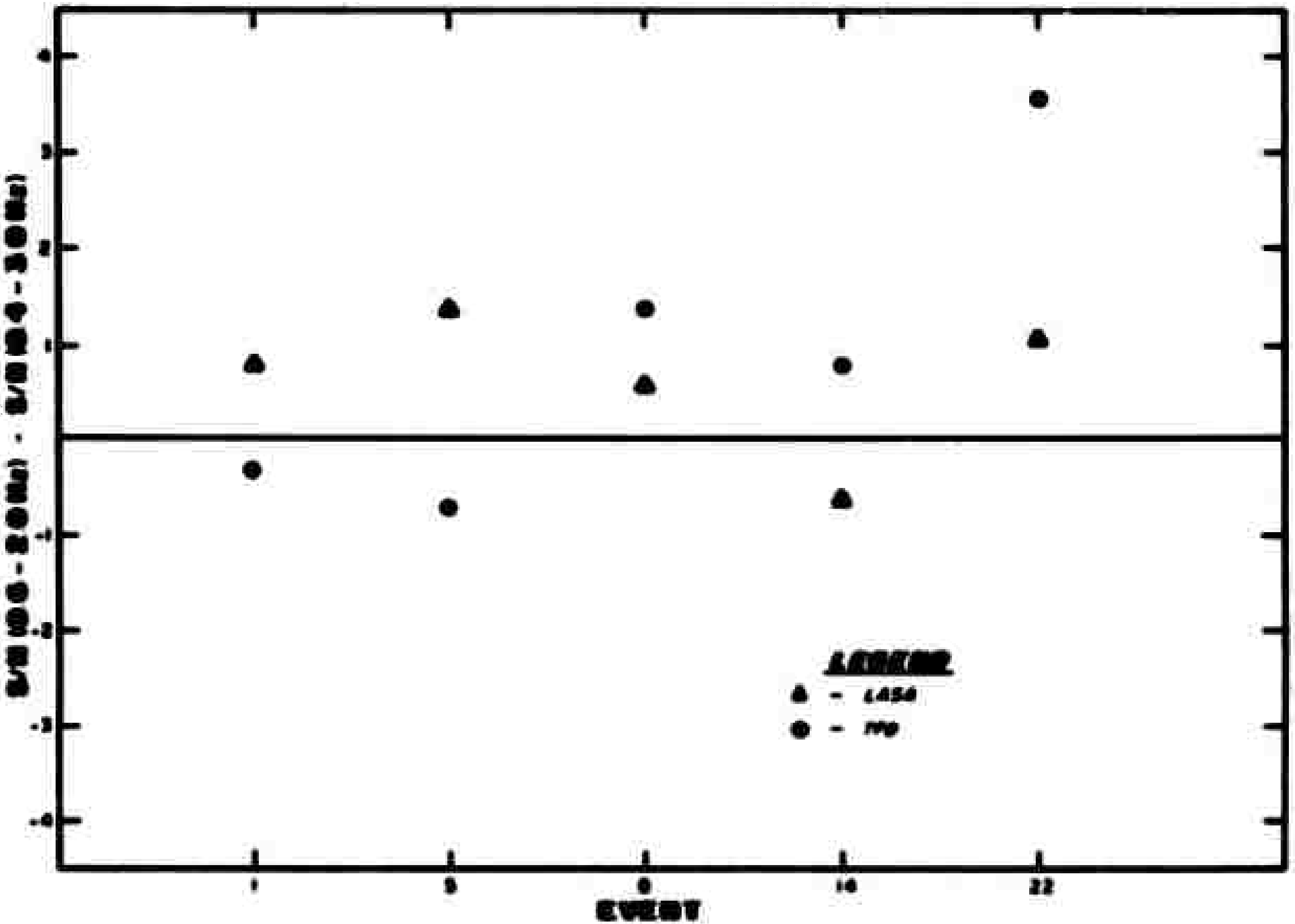

Figure 15. LASA beam S/N with band pass filter (0.[illegible]-2.0 Hz) minus S/N with band pass filter (0.4-3.0 Hz).

Figure 16. Relative positions of LASA E3 and TFO short period sensors used in the beam analysis.

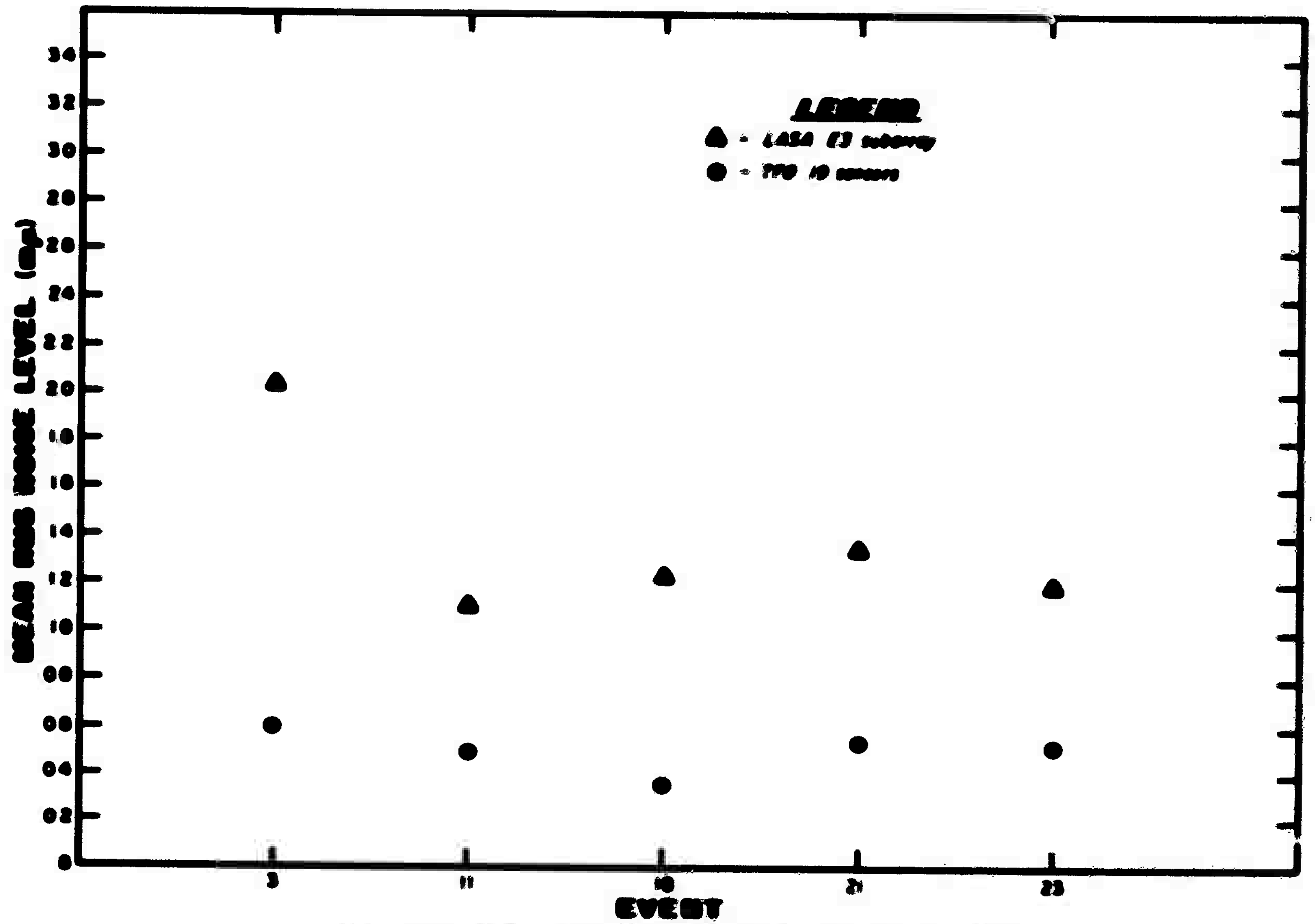

Figure 15. Mean short period rms noise levels at LASA E3 and TFO (Band pass filtered 0.4-3.0 Hz).

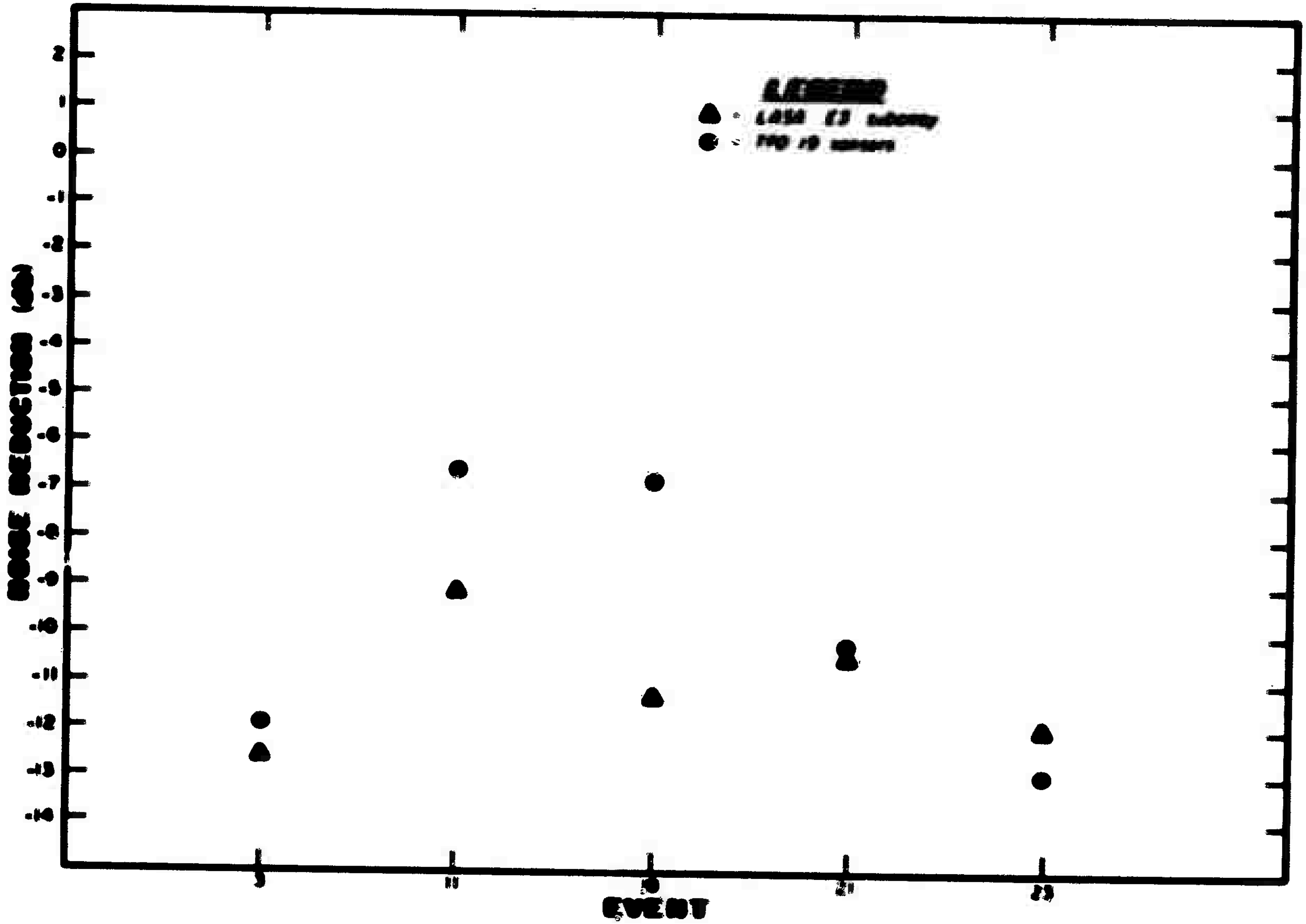

Figure 16. Noise reduction of short period beams of LASA E3 and TFO (Band pass filtered 0.4-3.0 Hz).

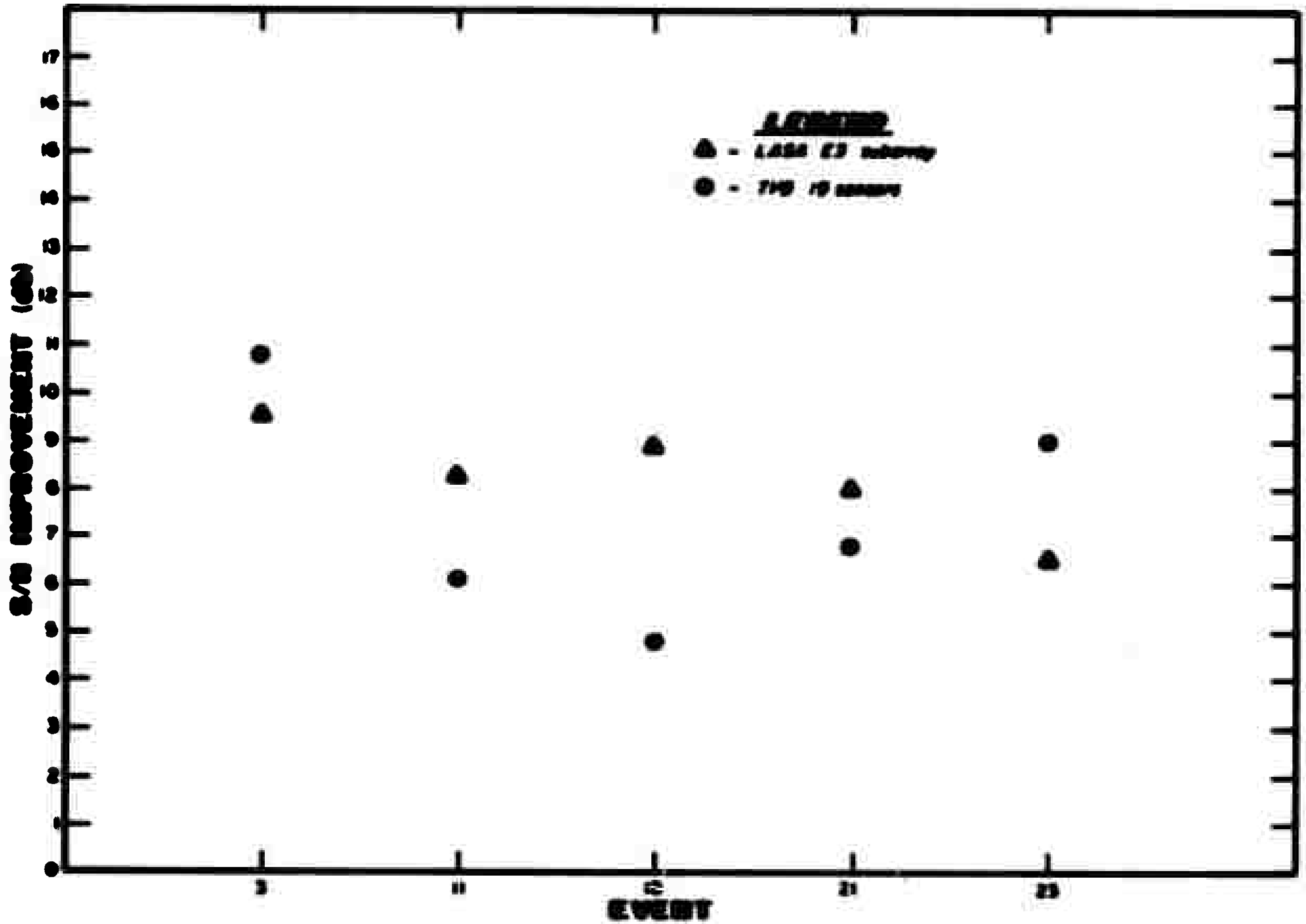

Figure 17. S/N improvement of short period beams of LASA E3 and TFO (Band pass filtered 0.4-3.0 Hz).

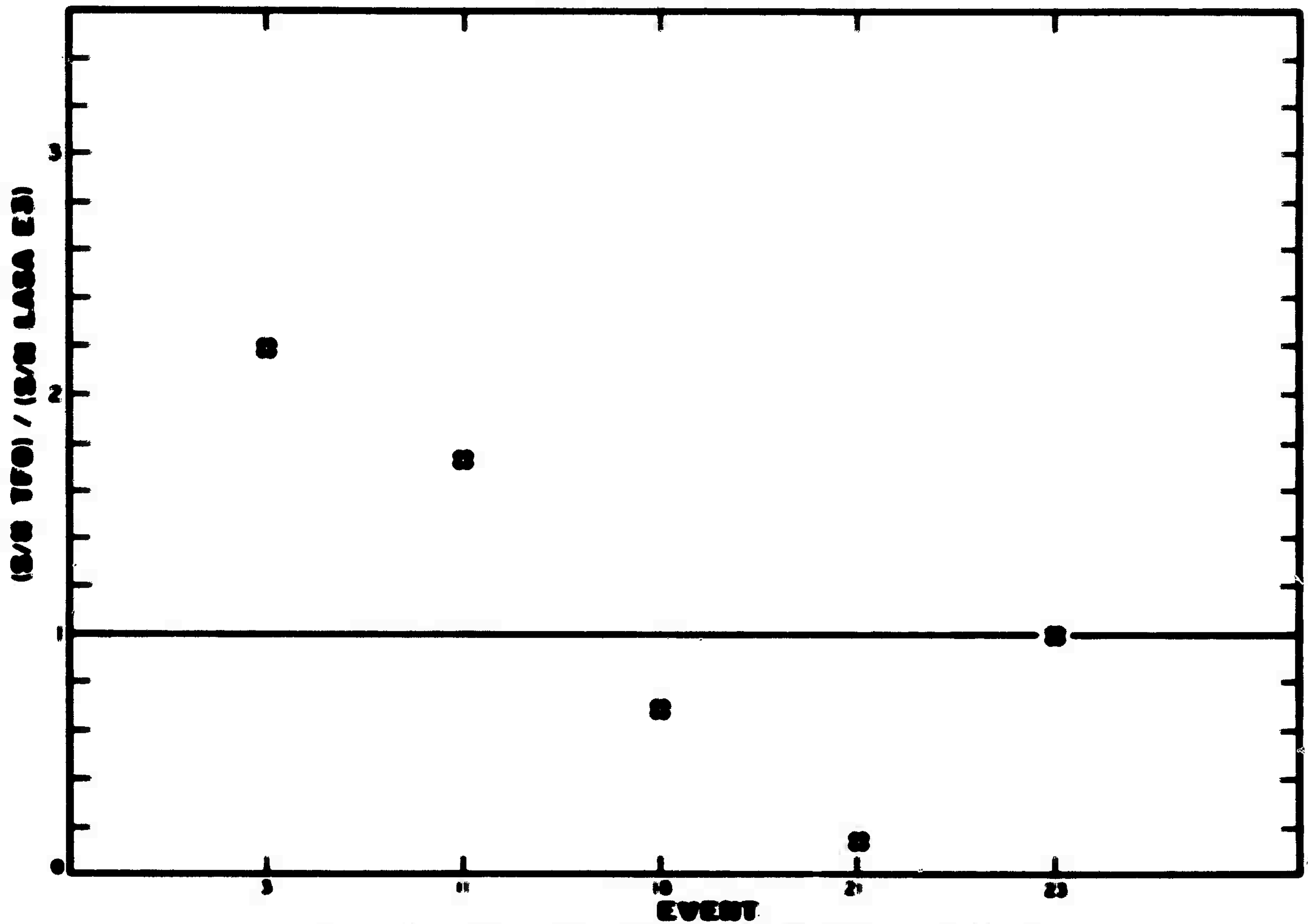

Figure 16. Ratio of the S/N for the TFO beam to the S/N for the LASA E3 beam (band pass filtered 0.4-3.0 Hz).

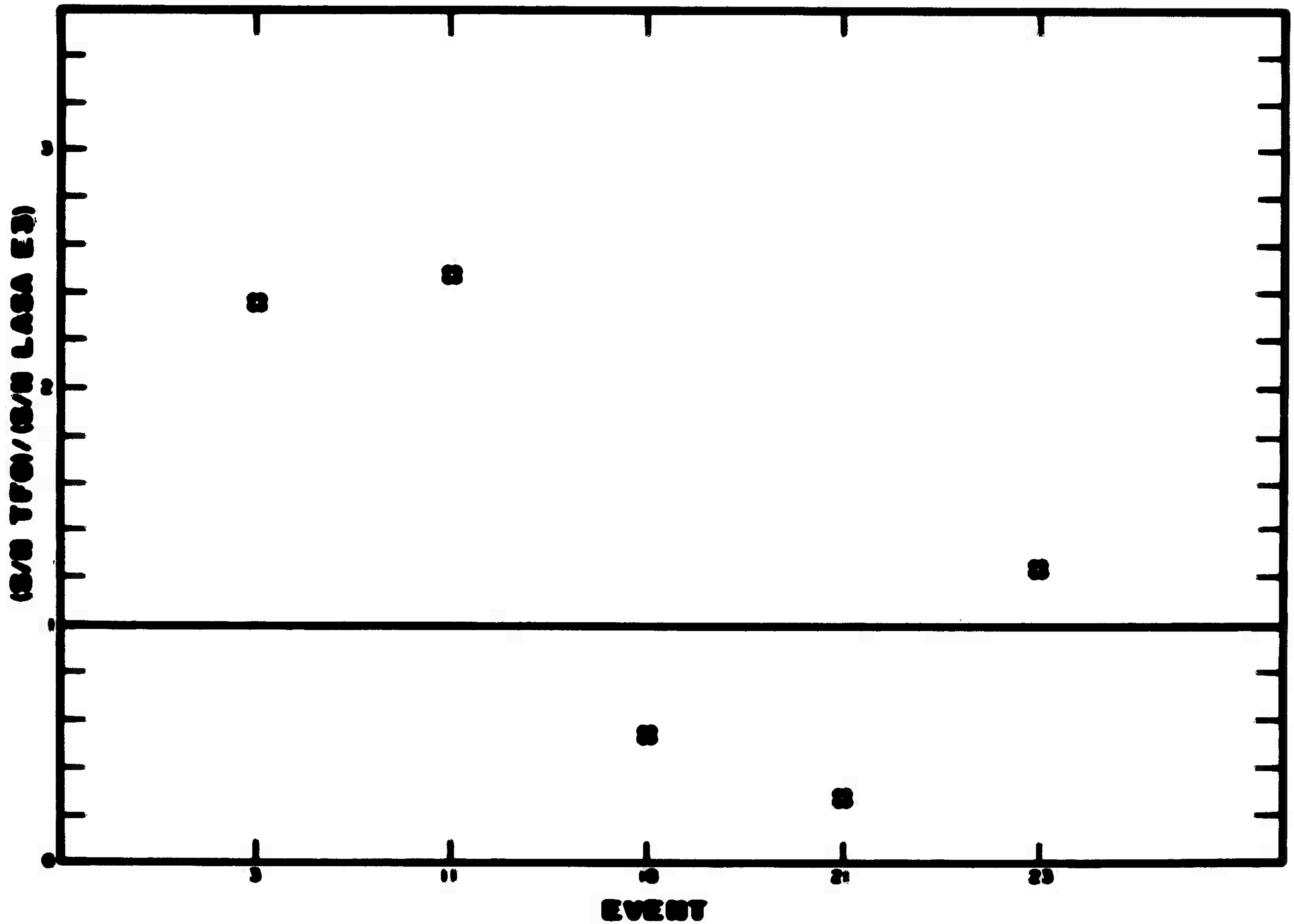

Figure 19. Ratio of the S/N for the TFO beam to the S/N for the LASA E3 beam corrected for the difference in epicentral distances to LASA and to TFO (band pass filtered 0.1-3.0 Hz).

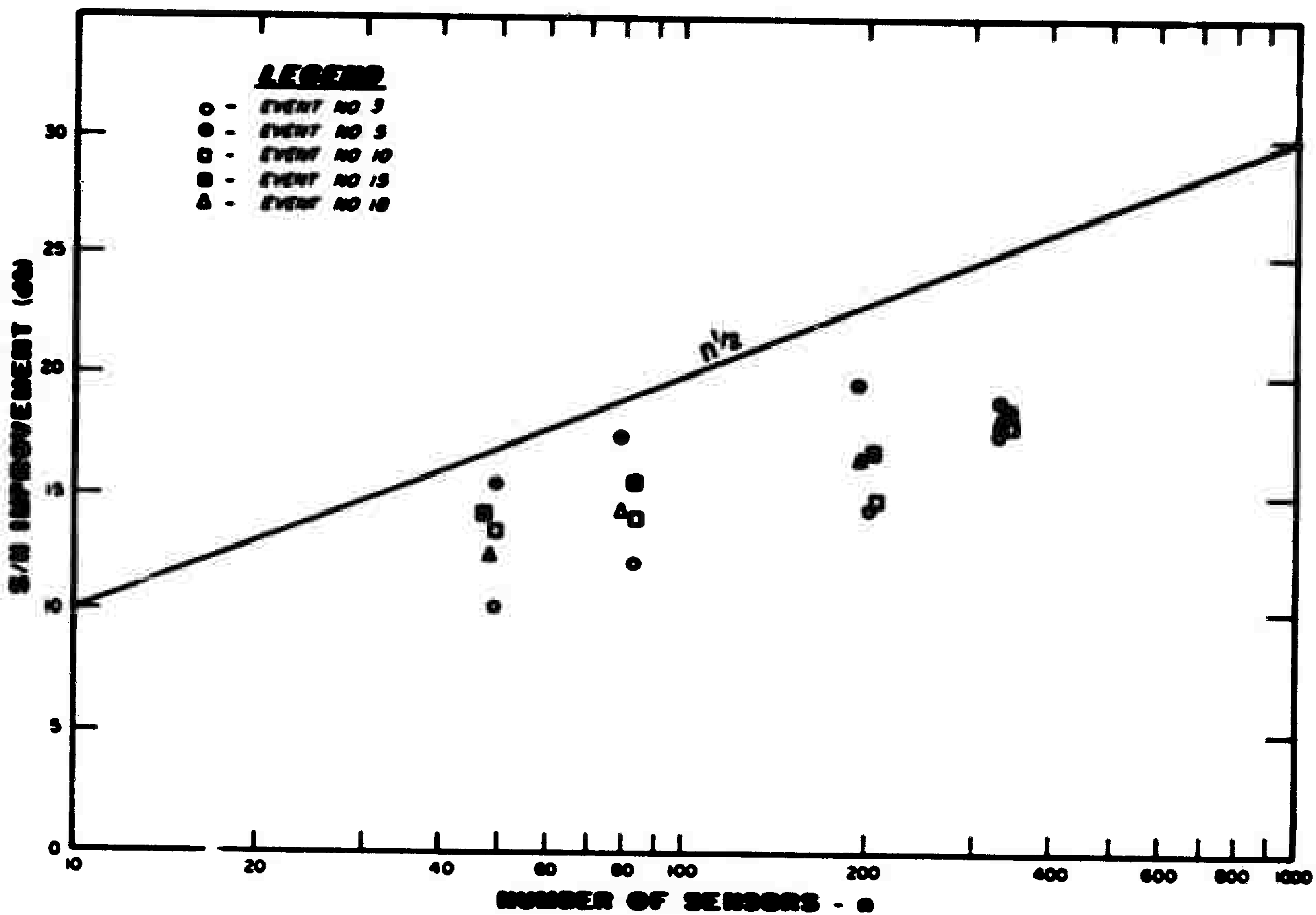

Figure 20. S/N improvement of short period beams of LASA for different sensor configurations (Band pass filtered 0.4-3.0 Hz).

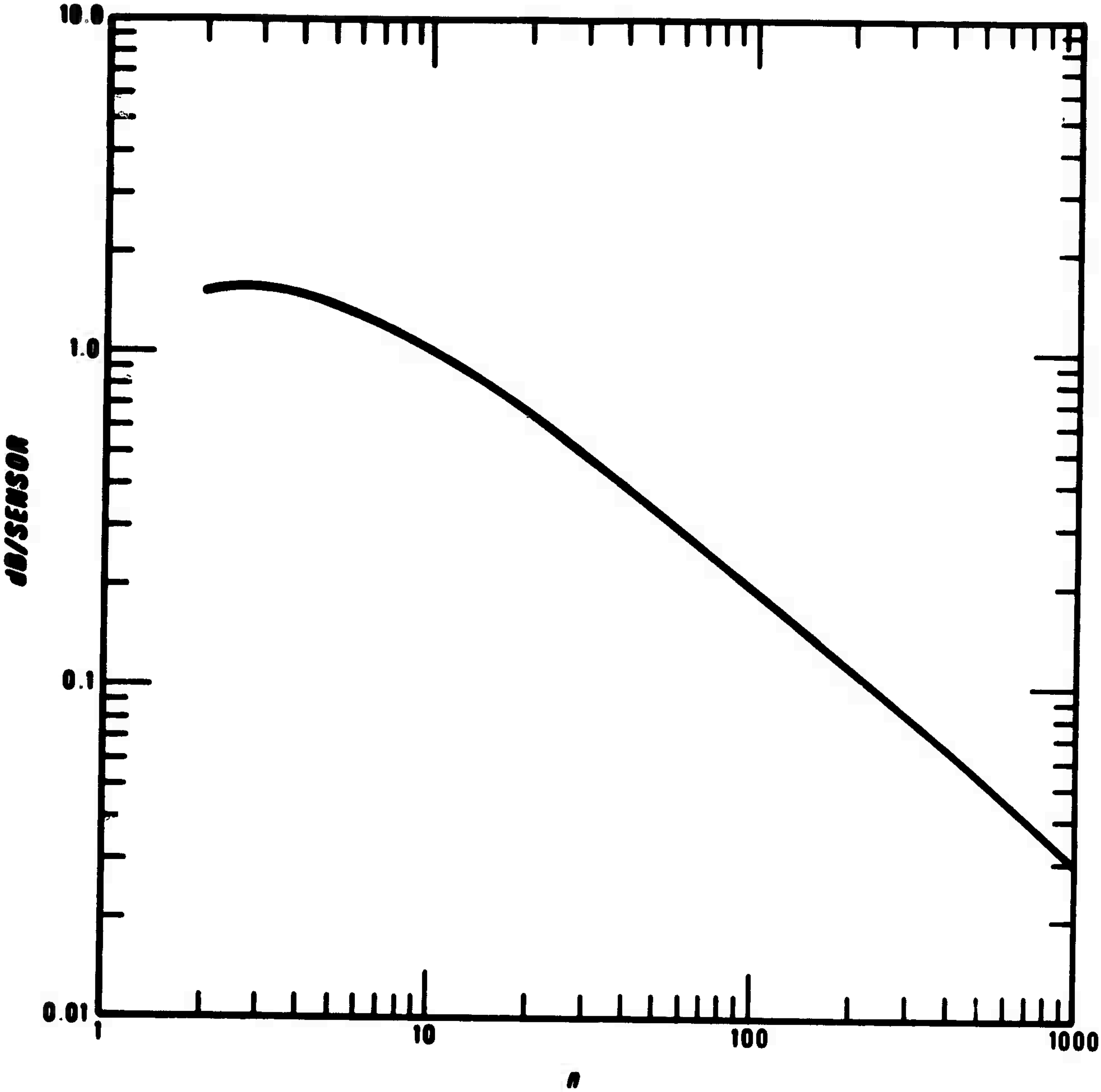

Figure 21. Efficiency of an array assuming $n^{1/2}$ noise reduction.